24152 DUP.

UNLIMITED
UNCLASSIFIED

ILLIMITÉ
NON CLASSIFIÉ

Technical Report

Rapport technique

1984/11

TR-MTC-002
NRC NO. 24152

LASER SURFACE HARDENING OF STEELS

M.U. Islam, W.J. Wells

Division of
Mechanical Engineering

Division de
génie mécanique

National Research Council Canada
Conseil national de recherches Canada

Canada

89-00584/

DIVISION OF MECHANICAL ENGINEERING PUBLICATIONS

DM **(Division of Mechanical Engineering Report)**
Scientific and technical information considered important, complete and a lasting contribution to existing knowledge.

TR **(Technical Report)**
Information less broad in scope but a substantial contribution to existing knowledge.

CTR **(Controlled/Classified Technical Report)**
A Technical Report with controlled distribution for national security, proprietary or other reasons.

LM **(Laboratory Memorandum)**
Preliminary or exploratory information with controlled distribution.

CAT **(Calibration Analysis and Test Report)**
Information on minor laboratory projects or services.

PUBLICATIONS DE LA DIVISION DE GÉNIE MÉCANIQUE

DM **(Rapport de la Division de génie mécanique)**
Informations scientifiques et techniques jugées importantes, complètes et susceptibles de contribuer de façon durable à l'avancement des connaissances courantes.

TR **(Rapport technique)**
Informations de moindre importance, mais pouvant contribuer substantiellement à l'avancement des connaissances actuelles.

CTR **(Rapport technique à diffusion contrôlée/classifiée)**
Rapport technique à diffusion contrôlée pour des raisons de sécurité nationale, de propriété intellectuelle et autres.

LM **(Mémoire de laboratoire)**
Informations préliminaires ou de nature exploratoire à diffusion contrôlée.

CAT **(Rapport d'étalonnage d'analyse et d'essai)**
Informations sur de petits projets ou des services de laboratoire.

UNLIMITED
UNCLASSIFIED

ILLIMITÉ
NON CLASSIFIÉ

LASER SURFACE HARDENING OF STEELS

DURCISSEMENT SUPERFICIEL AU LASER DES ACIERS

M. U. Islam, W. J. Wells

Technical Report
1984/11

Rapport technique
TR-MTC-002
NRC No. 24152

G. McGregor, Manager/Gérant
Manufacturing Technology Centre
Centre de technologie, fabrication

E. H. Dudgeon
Director/
Directeur

ACKNOWLEDGMENT

The authors would like to acknowledge the assistance of Mr. D. Koren, summer student assistant 1984, in obtaining the metallographic and micro-hardness data.

ABSTRACT

In this report, the laser hardening response of four steels: AISI 01, AISI 4340, carburized AISI 1020 and carburized AISI 9310, is studied in various prior heat treatment conditions. The laser operating parameter combinations are established to produce maximum hardened case depths without surface melting. The results indicate that a maximum hardened case depth of about 0.62 millimeters can be obtained by using laser beam power of 600 Watts and a scan rate of 0.21 centimeter per second. Moreover, quenched and tempered conditions with base hardnesses in the range of Rc 30 to 40 are ideally suited for the laser hardening process.

RÉSUMÉ

Dans le présent rapport, on étudie la réponse au durcissement au laser de quatre aciers ayant subi divers traitements thermiques préalables: AISI 01, AISI 4340, l'acier cémenté AISI 1020 et l'acier cémenté AISI 9310. Les paramètres de fonctionnement du laser sont combinés de façon à produire des profondeurs de cémentation maximales sans fusion superficielle. Les résultats montrent qu'on peut obtenir une profondeur de cémentation maximale d'environ 0,62 millimètre en utilisant un faisceau laser d'une puissance de 600 Watts et une vitesse de balayage de 0,21 centimètre par seconde. De plus, des aciers ayant subi une trempe ou un revenu préalable et ayant une dureté de base de l'ordre de 30 à 40 Rc conviennent très bien pour le durcissement au laser

CONTENTS

		Page
	ACKNOWLEDGMENT	(ii)
	ABSTRACT/RÉSUMÉ	(iii)
	CONTENTS	(iv)
	LIST OF TABLES	(v)
	LIST OF ILLUSTRATIONS	(v)
1.0	INTRODUCTION	1
2.0	EXPERIMENTAL DETAILS	3
3.0	RESULTS AND DISCUSSION	3
	3.1 Laser hardening response of AISI 01 tool steel	4
	3.2 Laser hardening response of AISI 4340 steel	6
	3.3 Laser hardening response of the carburized steels	7
4.0	CONCLUSIONS	8
5.0	REFERENCES	10

TABLES

Table		Page
1	Chemical composition (volume percent) of the steels used.	11
2	Heat treatments applied to the specimens prior to laser treating.	12
3	Laser power and traversing speed combinations used.	13
4	Laser surface hardening results for AISI O1 tool steel.	14
5	Laser surface hardening results for AISI 4340 steel.	15
6	Laser surface hardening results for the carburized AISI 1020 steel.	17

ILLUSTRATIONS

Figure		
1	Transverse section of a typical laser pass. Magnification - 20 X.	18
2	A typical laser hardened track on AISI O1 tool steel in 'as received' condition, along with the micro-hardness indentations. Magnification - 100 X. Laser power - 600 Watts. Traversing speed - 0.21 cm/sec.	19
3	Typical microstructure of the base material in 'as received' condition. Magnification - 1000 X.	20
4	The transition zone, the laser hardened zone (lighter) and the base material (darker). Un-dissolved carbides (white spots) in the laser hardened zone are also evident. Magnification - 1000 X. Laser power - 600 Watts. Traversing speed - 0.21 cm/sec.	21
5	Typical microstructure of the O1 tool steel specimens hardened and tempered at 426°C. Magnification - 1000 X.	22

6	Typical microstructure of the O1 tool steel specimens hardened and tempered at 537°C. Magnification - 1000 X.	23
7	Typical microstructure of the O1 tool steel specimens hardened and tempered at 621°C. Magnification - 1000 X.	24
8	The transition zone, the laser hardened zone (lighter) and the base material (darker) along with the micro-hardness indentations for the specimen C-25. Magnification - 200 X. Laser power - 600 Watts. Traversing speed - 0.21 cm/sec.	25
9	The transition zone, the laser hardened zone (lighter) and the base material (darker), along with micro-hardness indentations for the specimen C-12. Magnification - 200 X. Laser power - 600 Watts. Traversing speed - 0.42 cm/sec.	26
10	The transition zone, the laser hardened zone (lighter) and the base material (darker) of the specimen C-14. Magnification - 1000 X. Laser power - 600 Watts. Traversing speed - 0.42 cm/sec.	27
11	The Rockwell 'C' hardness versus the distance from the surface curves for the AISI O1 tool steel specimens irradiated by a 600 Watt laser beam and traversed at 0.21 cm/sec.	28
12	The Rockwell 'C' hardness versus the distance from the surface curves for the AISI O1 tool steel specimens irradiated by a 600 Watt laser beam and traversed at 0.42 cm/sec.	29
13	The Rockwell 'C' hardness versus the distance from the surface curves for the AISI O1 tool steel specimens irradiated by a 500 Watt laser beam and traversed at 0.21 cm/sec.	30
14	The Rockwell 'C' hardness versus the distance from the surface curves for the AISI O1 tool steel specimens irradiated by a 500 Watt laser beam and traversed at 0.42 cm/sec.	31

15	The Rockwell 'C' hardness versus the distance from the surface curves for the AISI 01 tool steel specimens irradiated by a 400 Watt laser beam and traversed at 0.21 cm/sec.	32
16	Typical microstructure of AISI 4340 steel quenched and tempered at 204°C. Magnification - 1000 X.	33
17	Typical microstructure of AISI 4340 steel quenched and tempered at 454°C. Magnification - 1000 X.	34
18	Typical microstructure of AISI 4340 steel quenched and tempered at 565°C. Magnification - 1000 X.	35
19	Typical transition zone for the AISI 4340 steel specimens hardened and tempered at 204°C. Magnification - 1000 X.	36
20	Typical transition zone for the AISI 4340 steel specimens hardened and tempered at 565°C. Magnification - 1000 X.	37
21	Typical transition zone for the AISI 4340 steel specimens in 'as received' condition, along with the micro-hardness indentations. Magnification - 500 X.	38
22	The Rockwell 'C' hardness versus the distance from the surface curves for the AISI 4340 steel specimens irradiated by a 600 Watt laser beam and traversed at 0.21 cm/sec.	39
23	The Rockwell 'C' hardness versus the distance from the surface curves for the AISI 4340 steel specimens irradiated by a 600 Watt laser beam and traversed at 0.42 cm/sec.	40
24	The Rockwell 'C' hardness versus the distance from the surface curves for the AISI 4340 steel specimens irradiated by a 500 Watt laser beam and traversed at 0.21 cm/sec.	41
25	The Rockwell 'C' hardness versus the distance from the surface curves for the AISI 4340 steel specimens irradiated by a 500 Watt laser beam and traversed at 0.42 cm/sec.	42
26	The Rockwell 'C' hardness versus the distance from the surface curves for the AISI 4340 steel specimens irradiated by a 400 Watt laser beam and traversed at 0.21 cm/sec.	43

27	Typical microstructure of the 'as carburized' case of AISI 1020 steel specimens. Magnification - 500 X.	44
28	Typical laser hardened zone (lighter) and the carburized case (darker) for the 'as carburized' AISI 1020 steel specimens. Magnification - 200 X.	45
29	Typical microstructure of the laser hardened zone for the 'as carburized' AISI 1020 steel specimens. Magnification - 500 X.	46
30	Typical laser hardened zone, transition zone and the carburized case of the quenched and tempered carburized AISI 1020 steel specimens. Magnification - 500 X.	47
31	The Rockwell 'C' hardness versus the distance from the surface curves for the carburized AISI 1020 steel specimens irradiated by a 600 Watt laser beam and traversed at 0.21 cm/sec.	48
32	The Rockwell 'C' hardness versus the distance from the surface curves for the carburized AISI 1020 steel specimens irradiated by a 600 Watt laser beam and traversed at 0.42 cm/sec.	49
33	The Rockwell 'C' hardness versus the distance from the surface curves for the carburized AISI 1020 steel specimens irradiated by a 500 Watt laser beam and traversed at 0.21 cm/sec.	50
34	The Rockwell 'C' hardness versus the distance from the surface curves for the carburized AISI 1020 steel specimens irradiated by a 500 Watt laser beam and traversed at 0.42 cm/sec.	51
35	The Rockwell 'C' hardness versus the distance from the surface curves for the carburized AISI 1020 steel specimens irradiated by a 400 Watt laser beam and traversed at 0.21 cm/sec.	52

LASER SURFACE HARDENING OF STEELS

1.0 INTRODUCTION:

The most widely used methods of increasing surface hardness, wear resistance, fatigue resistance and in some cases corrosion resistance of ferrous engineering components through heat treatment fall into two categories:

1. Thermo-chemical processes, in which elements such as carbon and nitrogen are introduced into the surface at elevated temperature, for example: carburizing, carbo-nitriding and nitriding.

2. Thermal processes in which heat alone is applied selectively to austenitize the surface, followed by quenching to produce a martensitic case, for example: induction or flame hardening.

In the second category, another recent addition is the use of high-powered lasers. Besides their more conventional application in welding, drilling and cutting, lasers are finding an increased use as a finely controllable heat source for selective surface hardening of steels [Ref.1-7]. Laser surface hardening offers the following general advantages over other conventional surface hardening techniques:

1. Very little or no work piece distortion due to minimal heat input and because the unaffected base metal serves to resist deformation.

2. Rapid production rates.

3. No external quenchant required.

4. Usually 100 percent martensite hardness by virtue of the severity of the self-quench mechanism.

5. Selective and/or precision heat treatment of complex shapes.

The beam from a carbon dioxide laser, having 10.6 micrometer wave length, is far infra-red and as such can be considered as pure heat energy. If the beam used has sufficient intensity, then upon its impingement, the surface of a ferrous material can achieve austenitization temperatures after a very short interaction time (a fraction of a second) while the bulk remains unaffected. Thus a very steep temperature gradient is created between the surface and the bulk of the material. Consequently, when the heat source is removed there is no need for an external quenchant to bring about the martensitic transformation in the case, the bulk of the material provides an adequate heat sink for "self quenching".

The relatively long 10.6 micrometer output wavelength of the carbon dioxide laser is not readily absorbed by most metallic materials. For instance, copper is over 95 percent reflective to this wave length and, as such, is widely used for laser reflective optics [Ref.8]. Smooth

steel surfaces are about 85 - 90 percent reflective [Ref.8]. Thus for an effective coupling of the laser energy, the surface of the steel should be coated with a material that is highly absorptive at 10.6 micrometer wavelength. The three most common coatings are of manganese or zinc phosphate [Ref. 5], powdered graphite suspension [Ref. 6] and spray paint (flat black). Of these, phosphates are the best absorbers, but are also most costly and time consuming to apply. Graphite is the poorest absorber and harder to apply than spray paint. It has been the experience at the Manufacturing Technology Centre that flat black spray paint provides adequate absorptive characteristics and is easy to apply, furthermore the laser hardening response of a steel coated in this way has been found to be relatively insensitive to the paint thickness.

Power density and exposure time are other important factors to be considered in the application of laser for heat treatment of steels. Beam power density is defined as the total beam power divided by the area over which it impinges on a surface. Since power density is the rate at which heat is delivered into the surface, high power densities could result in a very rapid surface temperature build-up. Insufficient time is available for heat to diffuse from the near surface into the underlying metal. This surface concentration of heat assures the rapid and precise formation of a hardened case. At the same time, the continued introduction of heat to the surface for an extended period of time permits the surface to reach the melting point, while the austenitizing isotherm is moving deeper into the part. The time for melting is relatively short (fraction of a second), and so the distance that the austenitizing isotherm can extend into the part is also limited. For this reason, depth of the hardened case is limited in the laser treatment, by the start of surface melting. On the other hand, lower power densities allow deeper case depths by virtue of the fact that the surface temperature is not rising as rapidly as with higher power densities. More time is available for heat to diffuse deeper into the part. Thus, the austenite zone can be driven deeper without surface melting. As can be expected, for sufficient metallurgical response, lower power densities require longer exposure times (slower scan rates) while higher power densities require short exposure times (faster scan rates).

The resistivity of the metal, beam impingement angle and the surface roughness and cleanliness are other minor factors that affect the absorption of the laser radiation by metals.

The resistivity of a metal relates directly to its absorptivity, because laser beam radiation interacts with electrons in the metal. It is reported [Ref.8] that the absorptivity at 10.6 microns is directly proportional to the square root of the resistivity. Resistivity increases with temperature, thus the hotter the work piece is, the more absorbing it is. This implies that the control of the work piece temperature is important in the laser heat treating for reproducible results.

Beam impingement angle on the work surface also affects beam absorption. Shallow impingement angles result in greater reflectivity. A normal (90 degrees) angle is considered optimal, but this may not always be possible due to complex work piece geometries.

Surface roughness and cleanliness are also considered to affect the laser beam absorption characteristics [Ref. 8]. An insulator such as an oxide layer on the surface of steel is reported to be a good coupler. Greater surface roughness can also promote absorption, but like the resistivity and the beam impingement angle, is not considered to be a major variable in the process of surface hardening of steels by lasers.

This report describes the results of an investigation conducted to study the hardening response of four steels, utilizing a 600 Watt (nominal) carbon dioxide laser at the Manufacturing Technology Center.

2.0 EXPERIMENTAL DETAILS:

In this investigation, the laser hardening response of four steels, AISI O1, AISI 4340, AISI 9310 (carburized) and AISI 1020 (carburized) with the chemical composition as listed in Table 1, is studied. Cubic specimens with 2.5 centimeters a side were machined from the 'as received' rods of suitable diameter. In order to determine the effects of prior microstructure on the laser hardening response, the specimens were heat treated according to the schedule shown in Table 2, giving 5 heat treatment conditions for AISI 4340, 4 heat treatment conditions for AISI O1, 3 heat treatment conditions each for AISI 1020 and AISI 9310, prior to laser treatment. The heat treated specimens were ground to provide a consistent surface finish and painted flat black to improve the laser absorption characteristics.

All the laser treatments were applied by using a special heat treatment lens of about 6.3 centimeter focal length. With this lens, the laser beam is focused in the form of a rectangle of about 0.7 centimeter length and 0.12 centimeter width, rather than a circular spot. For laser treating, the specimen was mounted on a micro-processor controlled X - Y table, and a single laser pass, with a beam impingement angle of 90 degrees, was made on each specimen. The laser power and traversing speed combinations used are shown in Table 3, giving 8 different laser parameter combination for each heat treatment condition of the steels used.

After laser treatments, all the specimens were sectioned, polished and etched for metallographic examination. Micro-hardness readings across the laser hardened track were taken by using a "LEITZ" micro-hardness tester with a 200 gram load. These diamond pyramid hardness values were then converted to Rockwell "C" values by a conventional conversion table [Ref. 9].

3.0 RESULTS AND DISCUSSION:

Figure 1 shows a typical transverse section of a single pass laser hardened zone at a lower magnification. As can be seen a distinct microstructural change has occured in this zone, indicating that the zone was heated above the austentizing temperature and the cooling rate was fast enough to produce martensitic transformation.

The metallographic and the micro-hardness results for each steel-used are discussed separately in the following sections.

3.1 LASER HARDENING RESPONSE OF AISI O1 TOOL STEEL:

The metallographic and the micro-hardness results of the laser treated specimens of O1 tool steel are shown in figures 2 to 15 and Table 4.

In figure 2, a typical laser hardened track for the specimens in 'as received' condition is shown along with micro-hardness indentations. The difference in hardness, as determined by the size of indentations, between the laser hardened zone and the base material is evident. Figure 3 shows the microstructure of the base material for the same specimen in 'as received' condition. As can be seen [Fig. 3], the base material is in a partially spheroidized condition. Cementite is present mostly in the form of fine spheroidized particles, however some lamellar cementite can also be seen in a matrix of ferrite. In figure 4, the transition from the laser hardened zone (lighter) to the base material is shown for the same specimen, which is rather gradual. The short duration of the austenitizing cycle is indicated by the presence of carbide particles (white spots in the laser hardened zone) which were not dissolved in the austenite during the high temperature cycle of the laser treatment. However, the matrix consists predominantly of martensite and probably some retained austenite in the laser hardened zone (lighter in Fig. 4).

Figures 5, 6 and 7 show the typical microstructures of the three hardened and tempered conditions applied to the O1 tool steel specimens-prior to the laser treatment. All the three microstructures are of tempered martensite produced by using three different tempering temperatures. Figure 5 shows a typical microstructure of the specimens tempered at a lower temperature of 426°C, as compared to the microstructures shown in figures 6 and 7, which are typical of the specimens tempered at higher temperatures of 537°C and 621°C respectively. Accordingly, the Rockwell 'C' hardness values decreased from Rc 48/50 for the specimens tempered at 426°C to Rc 38/40 for the specimens tempered at 537°C and Rc 28/30 for the specimens tempered at 621°C (Table 2).

Figures 8 and 9 show the laser hardened zone, base material and the micro-hardness indentations for the specimens C-25 (tempered at 426°C) and C-12 (tempered at 621°C) respectively. In figure 10, the microstructure of the transition zone for the specimen C-14 (tempered at 621°C) is shown. As is evident [Fig. 10], very little or no un-dissolved carbides are present in the laser hardened zone of the specimen which was hardened and tempered as compared to the laser hardened zone of the 'as received' specimen [Fig. 4] having a spheroidized microstructure.

Figures 11 to 15 establish the variation of Rockwell 'C' hardness as a function of the distance from the surface for laser hardened specimens of O1 tool steel in all the heat treatment conditions.

As is required of any surface hardening treatment, there should not be any associated surface melting. Thus the Rockwell 'C' versus the distance from the surface curves for all the laser parameters which produced any surface melting are not included in this report. Maximum hardness values in the range of Rockwell 'C' 62 to 68 are obtained in the laser hardened zone of all the AISI O1 tool steel specimens.

In Table 4, the results of all the O1 tool steel specimens are summarized along with the laser parameters applied. Effective case depth represents the distance from the surface up to which a minimum Rockwell 'C' value of 50 can be obtained [Ref. 9] and is estimated by Rockwell 'C' versus the distance from the surface plots for each specimen. The surface condition of each specimen is also characterized according to the degree of melting occurred due to the laser treatment as: large melt zone (M), small melt zone (SM) and no melt zone (NM).

Figures 11 and 12 show the Rockwell 'C' hardness as a function of the distance from the surface for O1 tool steel specimens, irradiated with a 600 Watt laser beam and traversed at 0.21 and 0.42 centimeters per second respectively, in all the heat treatment conditions used. As expected, increasing the traversing speed at the same power level produced slightly lower effective case depths. Similar observation can be made from Figures 13 and 14, which represent the O1 tool steel specimens irradiated with a laser beam of 500 Watts and traversed at a rate of 0.21 and 0.42 centimeters per second respectively. Figure 15 shows the hardness versus the distance from the surface curve for the lowest laser power used (400 Watts) at a scan rate of 0.21 centimeters per second. Another general observation is that, as expected, decreasing laser incident power at a given scan rate produced shallower effective case depths [Figures 11,13,15 and Table 4].

The effect of the initial microstructure on the effective case depth is also demonstrated in Figures 11 to 15 for the respective laser power and traversing speed combinations. Generally, the specimens tempered at a lower temperature (426°C) to produce higher base material hardness in the range Rc 48-50 (Table 2), showed 0.10 to 0.15 millimeters deeper case depths as compared to the other specimens treated with the same laser parameters. Furthermore, these specimens also show a pronounced softer region before the base material hardness is obtained after the transition zone, as indicated by the drop in hardness in their respective hardness versus the distance curves. This suggests that for the laser treatment, a more temper resistant base material is preferred. One way of increasing the temper resistance is to use a higher tempering temperature after quenching, prior to the laser hardening, as indicated by the results of the specimens tempered at 537°C and 621°C.

In short, the results clearly show that O1 tool steel responded very well to the laser surface hardening in all the prior heat treatment conditions. Laser parameters - 600 Watts at 0.21 or 0.42 centimeters per second, 500 Watts at 0.21 centimeter per second and 400 Watts at 0.21 centimeter per second produced comparable results without any sur-

face melting. Laser parameter 500 Watts at 0.42 centimeter per second produced the lowest effective case depths due to the lowest incident energy density (1.71 KJ/cm^2, Table-3) and can be considered as marginal. In terms of the incident energy densities (Table 3) and the effective case depth (Table 4), the laser parameter 600 Watts at 0.42 centimeters per second proved to be an optimum combination for surface hardening of O1 tool steel. With this combination, a minimum incident energy density (2.05 KJ/cm^2) is required to produce effective case depths in the range of 0.42 - 0.53 millimeters, which are comparable to the effective case depths produced by the laser parameters requiring higher incident energy densities (Tables 3 and 4).

3.2 LASER HARDENING RESPONSE OF AISI 4340 STEEL:

The metallographic and the micro-hardness results of all the AISI 4340 specimens are illustrated in Figures 16 to 26 and Table 5.

Figures 16, 17 and 18 show typical microstructures of AISI 4340 steel specimens quenched and tempered at 204°C, 454°C and 565°C respectively. All the microstructures predominantly consist of tempered martensite with probably some retained austenite. Figures 19 and 20 show typical transition zones for specimens tempered at 204°C and 565°C respectively. The carbide particles (white spots) which did not dissolve in the austenite during the heating portion of the laser treatment, are present in a larger quantity and nearer to the surface of the laser hardened specimen tempered at a higher temperature [Fig. 20] as compared to the specimen tempered at a lower temperature [Fig. 19].This may be attributed to the fact that higher tempering temperatures promote coarser carbide particles to grow, which may not dissolve in the austenite completely in the short time available at the austenitizing temperature during the laser treatment. In figure 21, a typical transition zone for the specimen in 'as received' condition is shown along with the microhardness indentations.

In Table 5, the laser surface hardening results are summerized for all the AISI 4340 steel specimens. It should be noted that the laser parameter combinations which did not produce any surface melting on AISI 4340 steel specimens (Table 5) are the same for AISI O1 tool steel specimens (Table 4). Laser parameter combinations : 600 Watts at 0.21 cm/sec, 600 Watts at 0.42 cm/sec, 500 Watts at 0.21 cm/sec and 400 Watts at 0.21 cm/sec produced comparable effective case depths in AISI 4340 steel specimens. Laser power and speed combination of 500 Watts at 0.42 cm/sec. again produced the lowest effective case depth due to the lowest incident energy density (Table-3).

In Figures 22 to 26, the variation in Rockwell 'C' hardness is established as a function of the distance from the surface for the laser parameter combinations that did not produce any surface melting in

the AISI 4340 steel specimens. Again the results are similar to those of AISI O1 tool steel specimens. Higher base material hardnesses tend to produce a distinct softer zone before base material hardness can be achieved after the laser hardened zone. However, it can be seen that AISI 4340 steel can be laser surface hardened to produce effective case depths in the range of 0.335 to 0.624 millimeters. Moreover, the Rockwell 'C' hardnesses (Rc 58-62) obtained in the laser hardened cases of the AISI 4340 steel specimens in all the hardened and tempered conditions are higher than those that can be obtained by any conventional method (Rc 50-54). These higher hardnesses obtained in the hardened zone of the specimens may be attributed to the decrease in the grain size and the extremely fine martensite resulting from a very short heating and cooling cycle during the laser treatment.

3.3 LASER HARDENING RESPONSE OF THE CARBURIZED STEELS:

The carburized AISI 1020 and AISI 9310 steels responded identically to the laser surface hardening, hence only the results of carburized AISI 1020 steel are described in this report.

The laser hardening results of the carburized AISI 1020 steel are illustrated in Figures 27 to 36 and listed in Table 6.

Figure 27 shows the typical microstructure of the 'as carburized' case of AISI 1020 steel specimens. Since the specimens in this condition were furnace cooled after carburizing, the microstructure of the carburized case predominantly consists of pearlite colonies surrounded by cementite near the specimen surface and by ferrite near the base material. The presence of grain boundary cementite in the carburized case indicate that the carbon potential of the furnace during the carburizing treatment was higher than 0.8% carbon (eutectoid composition).

In figure 28, typical laser hardened zone (lighter) is shown alongwith base material microstructure. In the base material (darker area) cementite (lighter) is present at the pearlite colony boundaries. In the laser hardened zone (lighter area) cementite can also be seen outlining the prior austenite grain boundaries. Figure 29 shows the laser hardened zone for the same specimen at a higher magnification. It can be seen that near the surface, grain boundary cementite as well as coarse cementite particles are not present, however they start to appear at about the center of the laser hardened zone. This indicates that the time and temperature combination during the laser treatment was adequate only up to half of the laser hardened zone depth, after which the austenitizing temperature was not held for a sufficiently long time to dissolve coarse carbides.

Figure 30 shows a typical laser hardened zone of quenched and tempered carburized specimens of AISI 1020 steel. As can be seen, in the laser hardened area (lighter) very little or no coarse cementite is

present. The transition zone appears to be rather large, and the base material (darker area) consists of tempered martensite.

In Table 6 the results of laser treatment are listed for all carburized AISI 1020 steel specimens with the respective laser parameter combinations used. It should be noted again (Table 6) that the laser parameter combinations that produced hardened cases in the carburized specimens without surface melting are the same as those reported for AISI O1 tool steel and AISI 4340 steels (Tables 4 and 5).

In figures 31 to 36, the variation of Rockwell 'C' hardness is plotted against the distance from the surface for all the laser parameter combinations that did not produce any surface melting. The Rockwell 'C' hardness versus the distance from the surface plots for the carburized steels can be characterized into the following three zones of constant hardness:

1. The highest hardness zone - This zone is produced by the laser treatment of the carburized zone and has hardness in the range of Rc 62-66.

2. The intermediate hardness zone - This is the carburized zone and extends up to around one millimeter (carburized case) below the surface. The hardness of this zone depends on the heat treatment applied before laser hardening process.

3. The lowest hardness zone (not indicated in the figures) - This zone represents the base material and its hardness also depends on the heat treatment applied before the laser hardening process.

The results clearly demonstrate that the laser treatment can be used to produce hardened cases up to 0.50 millimeters deep without surface melting in carburized steels (Table 6). The effective case depth obtained at a given laser power and speed combination is comparable for all the prior heat treatment conditions, suggesting that the prior microstructure does not have a significant effect. However, the microstructure and hence the properties of the laser hardened case primarily depend on the prior microstructure. The coarse prior microstructure (e.g as carburized) produced laser hardened zone consisting of coarse un-dissolved proeutectoid cementite at the prior austenite grain boundaries in a matrix of martensite. This microstructure may degrade the fatigue properties of the laser hardened steels. Quenched and tempered conditions, which produce fine spheroidal carbides in a matrix of martensite alleviate this problem.

4.0 CONCLUSIONS:

The following conclusions can be drawn from the results of this investigation:

1. AISI O1, AISI 4340, carburized 1020 and 9310 steels can all be surface hardened by using a 600 Watt (nominal) laser.

2. No external quenchant is required to bring about the martensitic transformation in the laser treated zone of all the steels used, and all the other advantages of the laser treatment as listed in the Introduction are also verified.

3. The following laser power and traversing speed combinations produced hardened cases without surface melting:

a) 600 Watts @ 0.21 cm/sec.
b) 600 Watts @ 0.42 cm/sec.
c) 500 Watts @ 0.21 cm/sec.
d) 500 Watts @ 0.42 cm/sec.
e) 400 Watts @ 0.21 cm/sec.

Generally, increasing the laser power at a given traversing speed and decreasing the traversing speed at a given laser power, produced a deeper effective case depth in all the steels used (Tables 4, 5 and 6).

4. Prior microstructure does not have a significant effect on the effective case depth produced by laser hardening.

5. Prior microstructure does effect the nature of the laser hardened zone. The quenched and tempered prior microstructures (finer) generally produced a more homogeneous laser hardened zone, while the normalized (coarse) prior microstructure produced laser hardened zone consisting of pro-eutectoid carbides in a matrix of martensite.

6. The laser treatment of the specimens in quenched and tempered conditions produced:

a) Softer regions between the laser hardened zone and the base material for the specimens tempered at a lower temperature to produce higher base material hardnesses ($>$Rc 40).

b) Un-dissolved carbides in the laser hardened zone of the specimens tempered at a higher temperature to produce lower base material hardness ($<$Rc 30).

It can hence be concluded that for all the steels used, quenched and tempered conditions with base material hardnesses in the range of Rc 30 to 40 are ideally suited for the laser surface hardening.

5.0 REFERENCES

1. Steen, W. M. Powel, J. — "Materials In Engineering" Vol. 2, No. 3, P.157, March 1981

2. Seaman, F. D. Gnanamuthu, D. S. — "Metal Progress" Vol. 108, No. 3, P.67, August 1975

3. Benedek, J. Shachrai, A. Levin, L. — "Optics and Laser Technology" Vol. 12, No. 5, P.247, October 1980

4. Belforte, D. A. — "Industrial °Heating" P.18. January 1982

5. Harth, G. H. Leslie, W. C. Gregson, V. G. Sanders, B. A. — "Journal of Metals" Vol. 20, No. 4, P.5, April 1976

6. Towers, S. A. — "Manufacturing Engineering" P. 145, August 1984

7. Steen, W. M. Courtney C. — "Metals Technology" Vol. 6, No. 6, P. 456, December 1979

8. Ready, J. F. — "Industrial Applications of Lasers" The Academic Press, 1978

9. — "Metals Handbook" The American Society of Metals. 8th Edition, Vol. 2, 1980

TABLE - 1
Chemical composition (volume percent) of the steels used.

ELEMENTS	AISI 01	AISI 4340	AISI 1020	AISI 9310
Carbon	0.9	0.38 - 0.43	0.18 - 0.23	0.08 - 0.13
Manganese	1.0 - 1.2	0.6 - 0.8	0.3 - 0.6	0.45 - 0.65
Phosphorous	---	0.04	0.04	0.025
Sulphur	---	0.04	0.04	0.025
Silicon	0.3	0.20 - 0.35	---	0.20 - 0.35
Nickel	---	1.65 - 2.00	---	3.00 - 3.50
Chromium	0.5	0.7 - 0.9	---	1.00 - 1.40
Molybdenum	---	0.2 - 0.3	---	0.08 - 0.15
Vanadium	0.2	---	---	---
Tungsten	0.5	---	---	---
Iron	Balance	Balance	Balance	Balance

TABLE - 2

Heat treatments given to the specimens prior to laser treating.

STEEL	HEAT TREATMENT APPLIED	ROCKWELL 'C' HARDNESS	MICROSTRUCTURE OBTAINED
AISI O1	As received	16 - 20	Spheroidized
	787°C - Oil quenched and tempered at:		
	a) 426°C	48 - 50	Tempered martensite
	b) 537°C	38 - 40	Tempered martensite
	c) 621°C	28 - 30	Tempered martensite
AISI 4340	As received	10 - 12	Spheroidized
	843°C -furnace cooled	22 - 24	Ferrite + Pearlite
	843°C -Oil quenched and tempered at:		
	a) 204°C	50 - 52	Tempered martensite
	b) 454°C	38 - 40	Tempered martensite
	c) 565°C	28 - 30	Tempered martensite
AISI 1020 and AISI 9310	Carburized at 926°C and furnace cooled.	18 - 20	Coarse pearlite in the case
	Carburized at 926°C oil quenched and tempered at:		
	a) 426°C	49 - 51	Tempered martensite
	b) 537°C	39 - 41	Tempered martensite

TABLE - 3
Laser power and traversing speed combinations used.

TREATMENT NUMBER	LASER POWER Watts	TRAVERSING SPEED cm/sec	EXPOSURE TIME seconds*	INCIDENT POWER DENSITY kW/cm^2**	INCIDENT ENERGY DENSITY kJ/cm^2***
1	600	0.42	0.24	8.57	2.05
2	600	0.21	0.47	8.57	4.02
3	500	0.42	0.24	7.14	1.71
4	500	0.21	0.47	7.14	3.35
5	500	0.04	2.50	7.14	17.85
6	400	0.21	0.47	5.71	2.68
7	400	0.04	2.50	5.71	14.27
8	400	0.02	5.00	5.71	28.55

$$* \text{ EXPOSURE TIME (seconds)} = \frac{\text{Beam width (0.1 cm)}}{\text{Traversing speed}}$$

$$** \text{ INCIDENT POWER DENSITY } (kW/cm^2) = \frac{\text{Power}}{0.7 \times 0.1 \times 1000}$$

$$*** \text{ INCIDENT ENERGY DENSITY } (kJ/cm^2) = \frac{\text{Power} \times \text{Exposure time}}{0.7 \times 0.1 \times 1000}$$

TABLE - 4
Laser surface hardening results for AISI O1 tool steel.

SPECIMEN NUMBER	HEAT TREATMENT CONDITION	ROCKWELL 'C' HARDNESS	LASER POWER Watts	TRAVERSING SPEED cm/sec	EFFECTIVE CASE DEPTH mm	SURFACE CONDITION
C-1	As received	18	600	0.21	0.495	NM
C-13	Hdn.&temp.	30	600	0.21	0.520	NM
C-11	Hdn.&temp.	41	600	0.21	0.482	NM
C-25	Hdn.&temp.	49	600	0.21	0.571	NM
C-2	As received	19	600	0.42	0.426	NM
C-14	Hdn.&temp.	28	600	0.42	0.426	NM
C-12	Hdn.&temp.	40	600	0.42	0.431	NM
C-26	Hdn.&temp.	50	600	0.42	0.533	NM
C-3	As received	20	500	0.04	-	M
C-23	Hdn.&temp.	29	500	0.04	0.546	SM
C-15	Hdn.&temp.	41	500	0.04	0.807	M
C-27	Hdn.&temp.	49	500	0.04	0.827	M
C-4	As received	19	500	0.21	0.406	NM
C-24	Hdn.&temp.	29	500	0.21	0.467	NM
C-16	Hdn.&temp.	39	500	0.21	0.543	NM
C-28	Hdn.&temp.	50	500	0.21	0.598	NM
C-5	As received	20	500	0.42	0.299	NM
C-29	Hdn.&temp.	30	500	0.42	0.198	NM
C-17	Hdn.&temp.	40	500	0.42	0.391	NM
C-31	Hdn.&temp.	49	500	0.42	0.330	NM
C-6	As received	19	400	0.02	0.609	M
C-30	Hdn.&temp.	28	400	0.02	0.482	M
C-18	Hdn.&temp.	41	400	0.02	0.802	M
C-32	Hdn.&temp.	50	400	0.02	0.543	M
C-7	As received	20	400	0.04	0.518	SM
C-35	Hdn.&temp.	30	400	0.04	0.497	SM
C-19	Hdn.&temp.	40	400	0.04	0.604	SM
C-33	Hdn.&temp.	50	400	0.04	0.665	SM
C-8	As received	19	400	0.21	0.360	NM
C-36	Hdn.&temp.	29	400	0.21	0.396	NM
C-20	Hdn.&temp.	41	400	0.21	0.411	NM
C-34	Hdn.&temp.	50	400	0.21	0.447	NM

Hdn.&Temp. - Hardened and Tempered.
NM - No melt. SM - Small melt zone. M - Large melt zone.
EFFECTIVE CASE DEPTH - Case depth up to which a minimum value of Rockwell 'C' 50 is obtained.

TABLE - 5
Laser surface hardening results for AISI 4340 steel.

SPECI-MEN NUMBER	HEAT TREATMENT CONDITION	ROCKWELL 'C' HARDNESS	LASER POWER Watts	TRAVERSING SPEED cm/sec	EFFECTIVE CASE DEPTH mm	SURFACE CONDITION
B-5	As received	10-12	600	0.21	0.538	NM
B-19	Normalized	18-21	600	0.21	0.579	NM
B-11	Hdn.& Temp.	28-31	600	0.21	0.574	NM
B-9	Hdn.& Temp.	39-41	600	0.21	0.609	NM
B-15	Hdn.& Temp.	49-51	600	0.21	0.624	NM
B-6	As received	10-12	600	0.42	0.457	NM
B-20	Normalized	18-21	600	0.42	0.513	NM
B-12	Hdn.& Temp.	28-31	600	0.42	0.492	NM
B-10	Hdn.& Temp.	39-41	600	0.42	0.482	NM
B-16	Hdn.& Temp.	49-51	600	0.42	0.538	NM
B-51	As received	10-12	500	0.04	0.614	SM
B-33	Normalized	18-21	500	0.04	0.716	SM
B-21	Hdn.& Temp.	28-31	500	0.04	0.800	SM
B-13	Hdn.& Temp.	39-41	500	0.04	0.617	SM
B-23	Hdn.& Temp.	49-51	500	0.04	0.652	SM
B-52	As received	10-12	500	0.21	0.457	NM
B-34	Normalized	18-21	500	0.21	0.558	NM
B-24	Hdn.& Temp.	28-31	500	0.21	0.523	NM
B-14	Hdn.& Temp.	39-41	500	0.21	0.472	NM
B-22	Hdn.& Temp.	49-51	500	0.21	0.518	NM
B-35	As received	10-12	500	0.42	0.335	NM
B-37	Normalized	18-21	500	0.42	0.411	NM
B-25	Hdn.& Temp.	28-31	500	0.42	0.431	NM
B-17	Hdn.& Temp.	39-41	500	0.42	0.411	NM
B-27	Hdn.& Temp.	49-51	500	0.42	0.401	NM
B-36	As received	10-12	400	0.02	0.726	M
B-38	Normalized	18-21	400	0.02	0.683	M
B-28	Hdn.& Temp.	28-31	400	0.02	0.779	M
B-18	Hdn.& Temp.	39-41	400	0.02	0.596	M
B-26	Hdn.& Temp.	49-51	400	0.02	0.614	M
B-61	As received	10-12	400	0.04	0.518	SM
B-53	Normalized	18-21	400	0.04	0.716	SM
B-41	Hdn.& Temp.	28-31	400	0.04	0.645	SM
B-45	Hdn.& Temp.	39-41	400	0.04	0.845	SM
B-29	Hdn.& Temp.	49-51	400	0.04	0.706	SM

continued on next page.....

TABLE - 5 continued.

SPECIMEN NUMBER	HEAT TREATMENT CONDITION	ROCKWELL 'C' HARDNESS	LASER POWER Watts	TRAVERSING SPEED cm/sec	EFFECTIVE CASE DEPTH mm	SURFACE CONDITION
B-62	As received	10-12	400	0.21	0.441	NM
B-54	Normalized	18-21	400	0.21	0.508	NM
B-30	Hdn.& Temp.	28-31	400	0.21	0.538	NM
B-46	Hdn.& Temp.	39-41	400	0.21	0.553	NM
B-42	Hdn.& Temp.	49-51	400	0.21	0.548	NM

Hdn.& Temp. - Hardened and tempered specimens.
NM - No melt. SM - Small melt zone. M - Large melt zone.

TABLE - 6

Laser surface hardening results for carburized AISI 1020 steel.

SPECIMEN NUMBER	HEAT TREATMENT CONDITION	ROCKWELL 'C' HARDNESS	LASER POWER Watts	TRAVERSING SPEED cm/sec	EFFECTIVE CASE DEPTH mm	SURFACE CONDITION
A-1	As carb.	18-20	600	0.21	0.487	NM
A-11	Hdn.& Temp.	49-51	600	0.21	0.482	NM
A-17	Hdn.& Temp.	40-43	600	0.21	0.508	NM
A-2	As carb.	18-20	600	0.42	0.416	NM
A-12	Hdn.& Temp.	49-51	600	0.42	0.462	NM
A-18	Hdn.& Temp.	40-43	600	0.42	0.436	NM
A-3	As carb.	18-20	500	0.04	0.527	SM
A-13	Hdn.& Temp.	49-51	500	0.04	0.584	SM
A-21	Hdn.& Temp.	40-43	500	0.04	0.574	SM
A-4	As carb.	18-20	500	0.21	0.426	NM
A-14	Hdn.& Temp.	49-51	500	0.21	0.436	NM
A-22	Hdn.& Temp.	40-43	500	0.21	0.431	NM
A-5	As carb.	18-20	500	0.42	0.254	NM
A-15	Hdn.& Temp.	49-51	500	0.42	0.304	NM
A-25	Hdn.& Temp.	40-43	500	0.42	0.345	NM
A-6	As carb.	18-20	400	0.02	0.624	M
A-16	Hdn.& Temp.	49-51	400	0.02	0.680	M
A-26	Hdn.& Temp.	40-43	400	0.02	0.645	M
A-7	As carb.	18-20	400	0.04	0.518	SM
A-19	Hdn.& Temp.	49-51	400	0.04	0.574	SM
A-27	Hdn.& Temp.	40-43	400	0.04	0.528	SM
A-8	As carb.	18-20	400	0.21	0.411	NM
A-20	Hdn.& Temp.	49-51	400	0.21	0.401	NM
A-28	Hdn.& Temp.	40-43	400	0.21	0.416	NM

As carb. -- As carburized. Hdn.& Temp. -- Hardened and tempered
NM -- No melt. SM -- Small melt zone. M -- Large melt zone.
Note; The Rockwell 'C' hardness values are for the surface only.

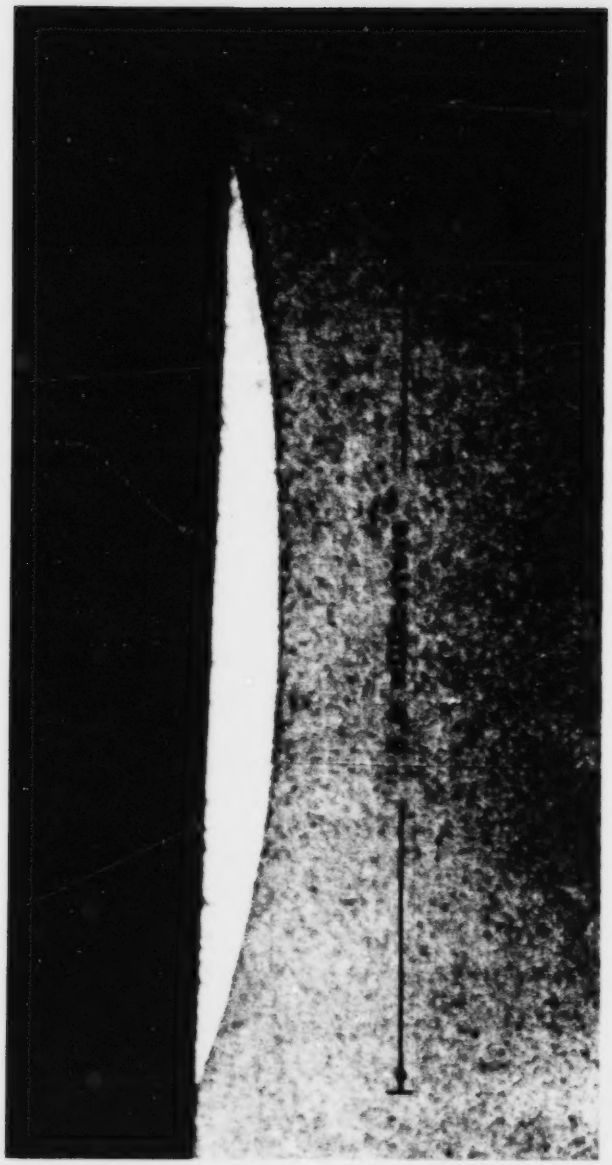

Figure 1 Transverse Section of a Typical Laser Pass. Magnification 20X.

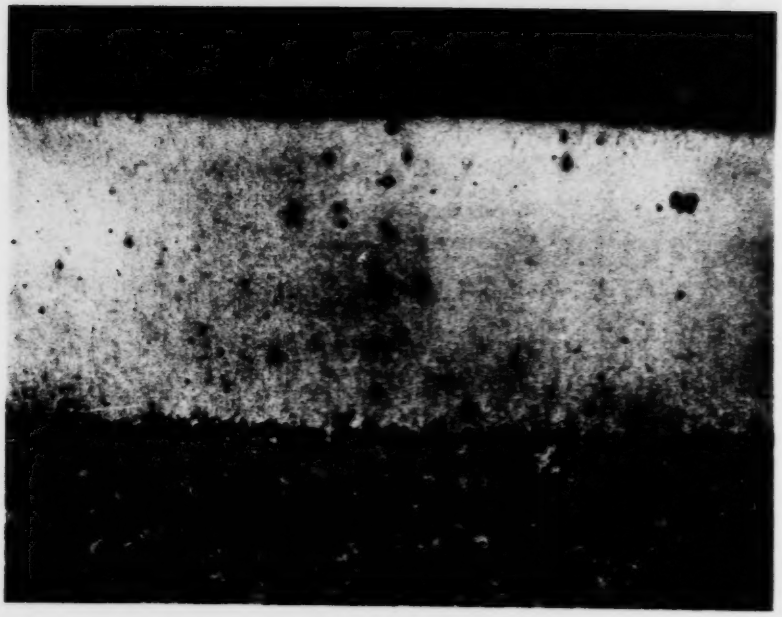

Figure 2. A typical laser hardened track on 01 tool steel specimens in 'as received' condition along with micro-hardness indentations.
Magnification - 100X
Laser power - 600 Watts.
Traversing speed - 0.21 cm/sec.

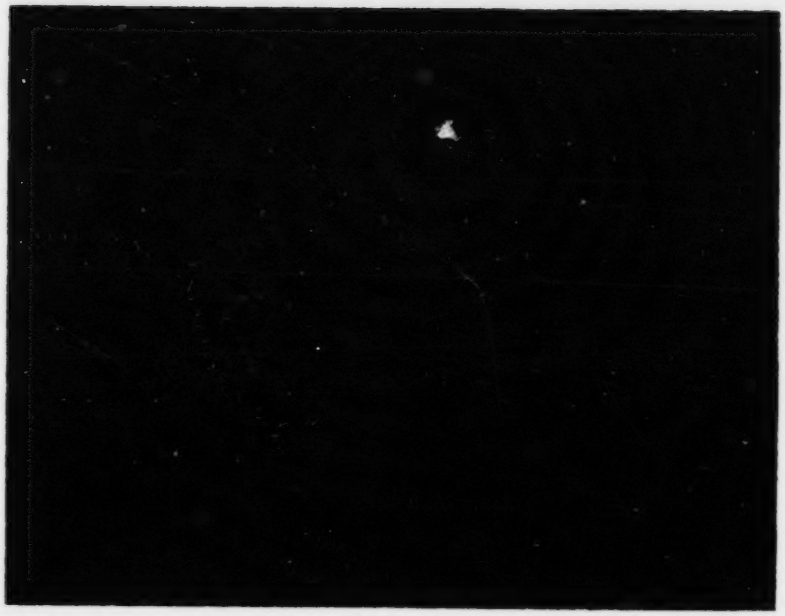

Figure 3. Typical microstructure of the base material in 'as received' condition. Magnification - 100X.

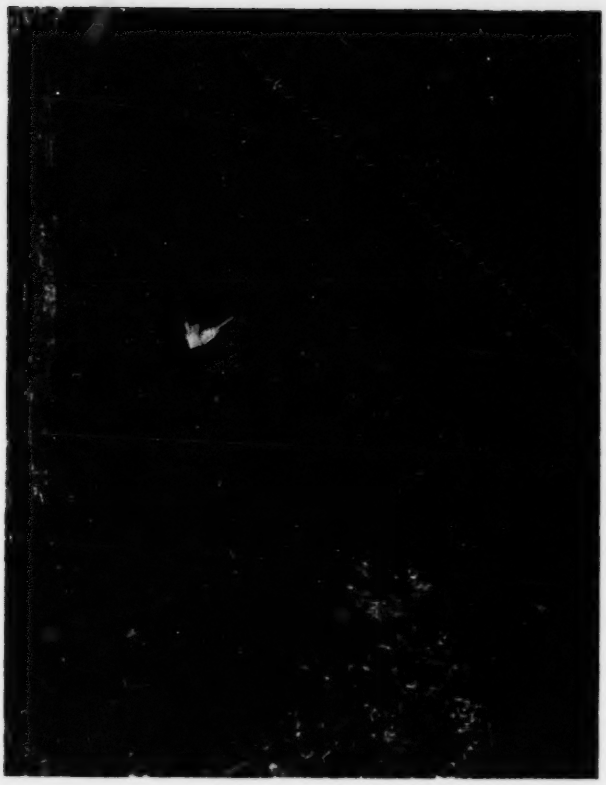

Figure 4: The transition zone, the laser hardened zone (lighter) and the base material (darker). Un-dissolved carbides (white spots) in the laser hardened zone are also evident.
Magnification - 1000X.
Laser power - 600 Watts.
Traversing speed - 0.21 cm/sec.

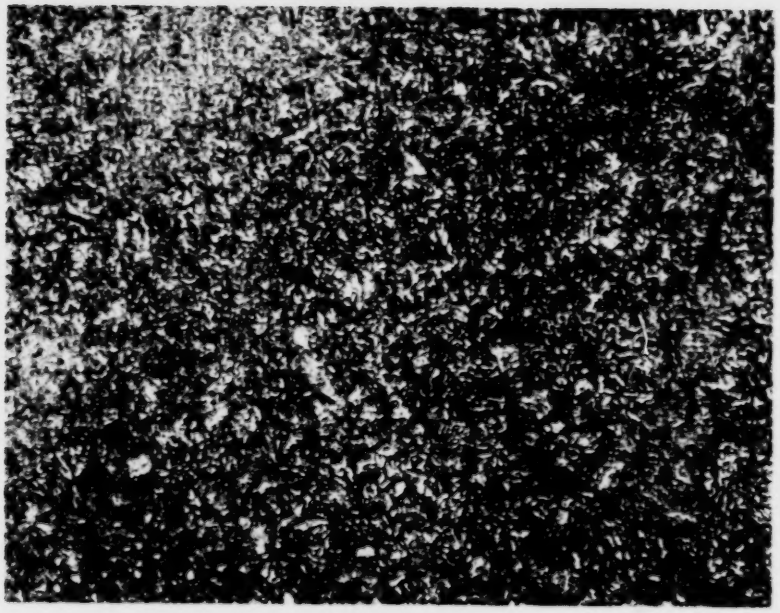

Figure 5: Typical microstructure of the 01 tool steel specimens, hardened and tempered at 426°C Magnification - 1000X.

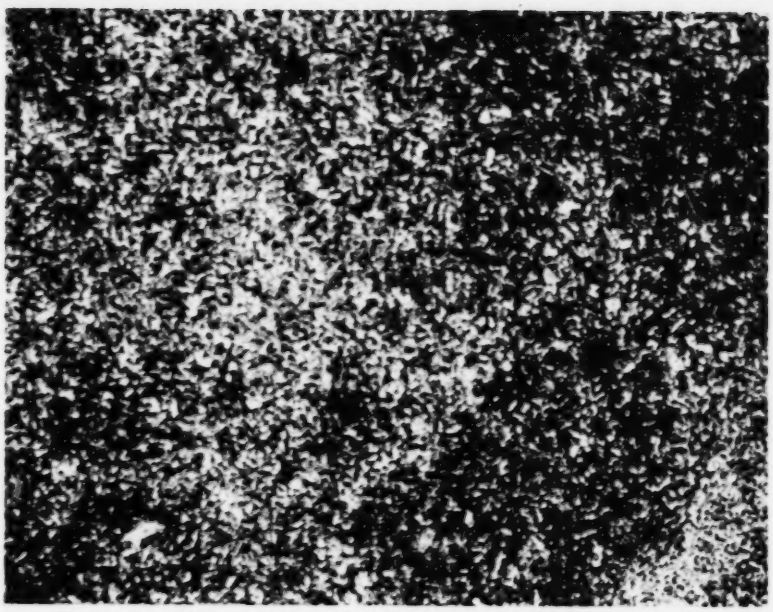

Figure 6: Typical microstructure of the 01 tool steel specimens, hardened and tempered at 537°C Magnification -1000X.

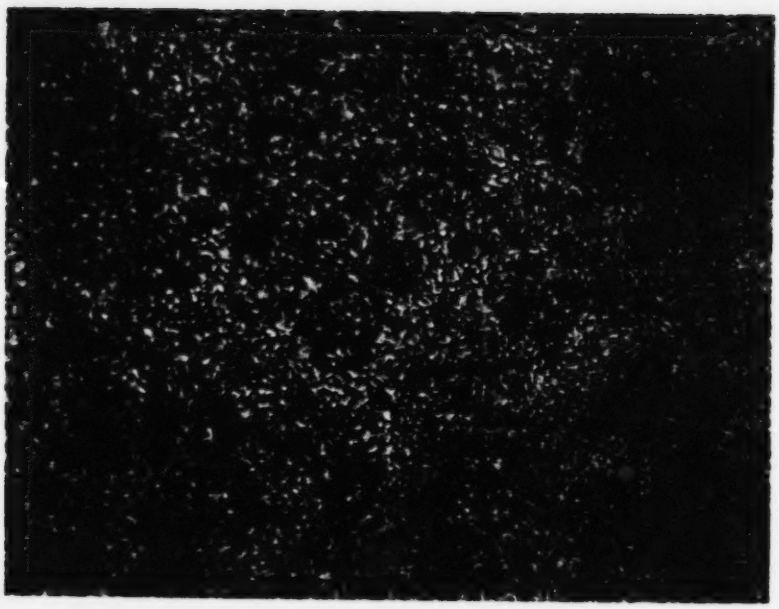

Figure 7: Typical microstruture of the O1 tool steel specimens, hardened and tempered at 621°C. Magnification - 1000X.

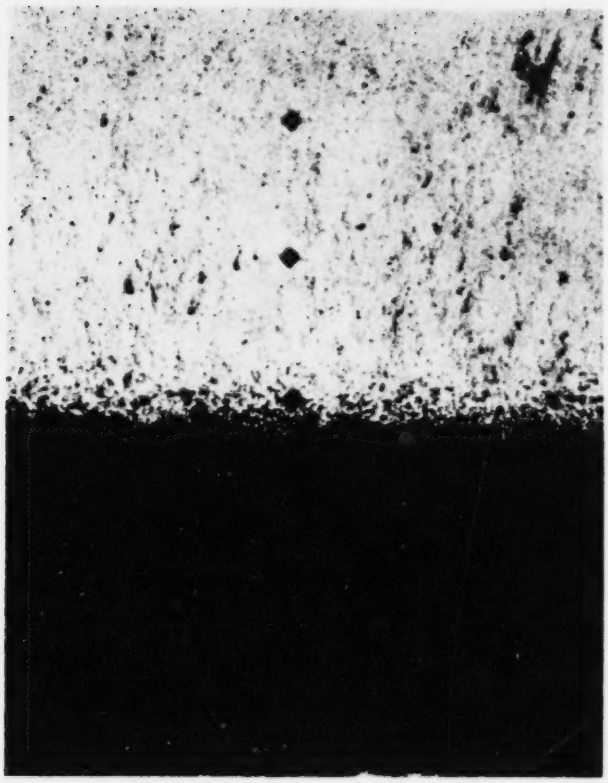

Figure 8: The transition zone, the laser hardened zone (lighter) and the base material (darker), along with the micro-hardness indentations for the specimen C-25.
Magnification - 200X.
Laser power - 600 Watts.
Traversing speed - 0.21 cm/sec.

Figure 9: The transition zone, the laser hardened zone (lighter) and the base material (darker), along with the micro-hardness indentations for the specimen C-12.
Magnification - 200X.
Laser power - 600 Watts.
Traversing speed - 0.42 cm/sec.

Figure 10: The transition zone, the laser hardened zone (lighter) and the base material (darker) of the specimen C-14.
Magnification - 1000X.
Laser power - 600 Watts.
Traversing speed - 0.42 cm/sec.

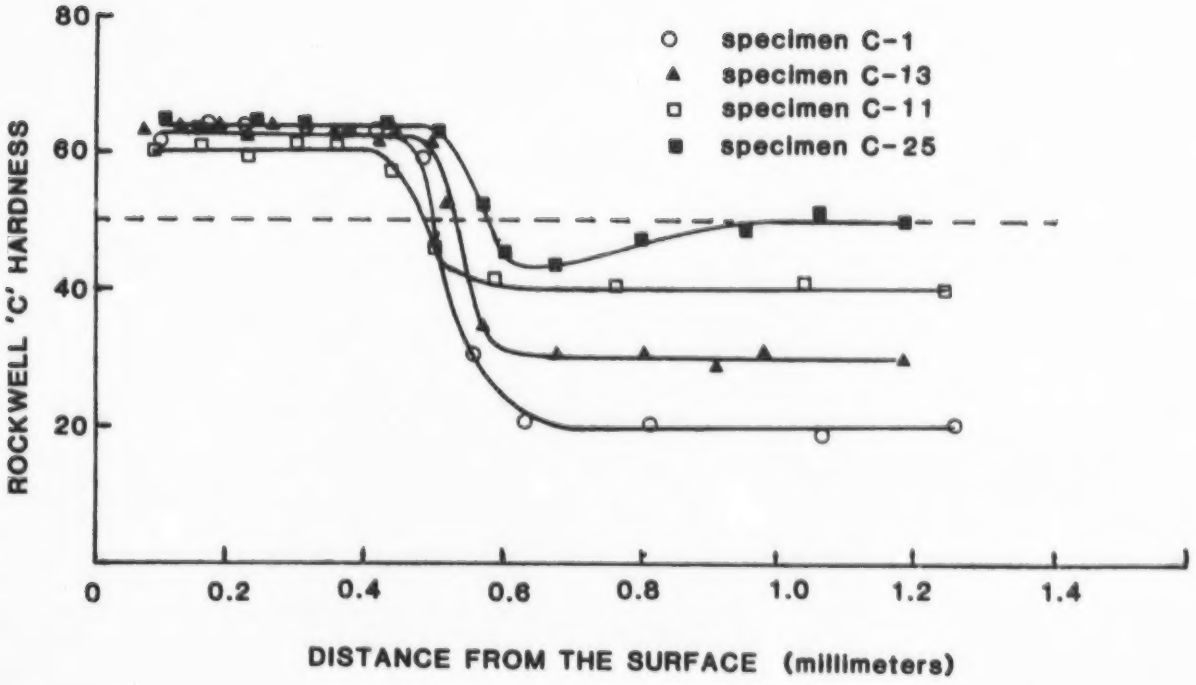

Figure 11: The Rockwell 'C' hardness versus the distance from the surface curves for the AISI 01 tool steel specimens irradiated by a 600 Watt laser beam and traversed at 0.21 cm/sec.

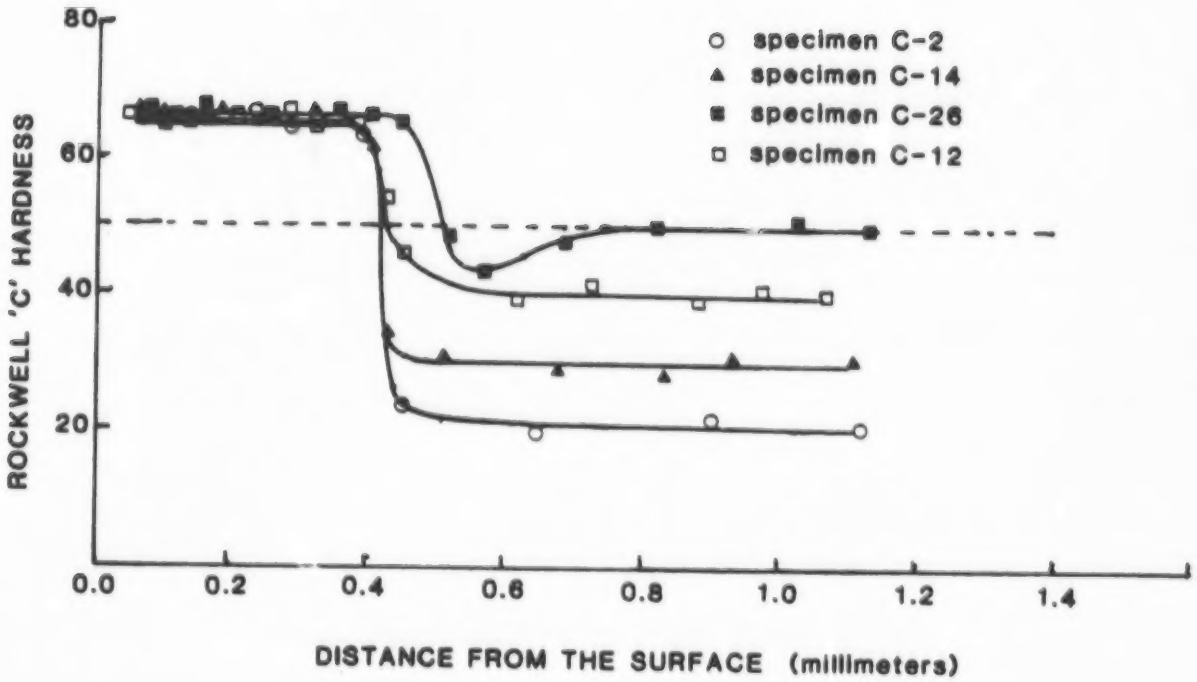

Figure 12: The Rockwell 'C' hardness versus the distance from the surface curves for the AISI 01 tool steel specimens irradiated by a 600 Watt laser beam and traversed at 0.42 cm/sec.

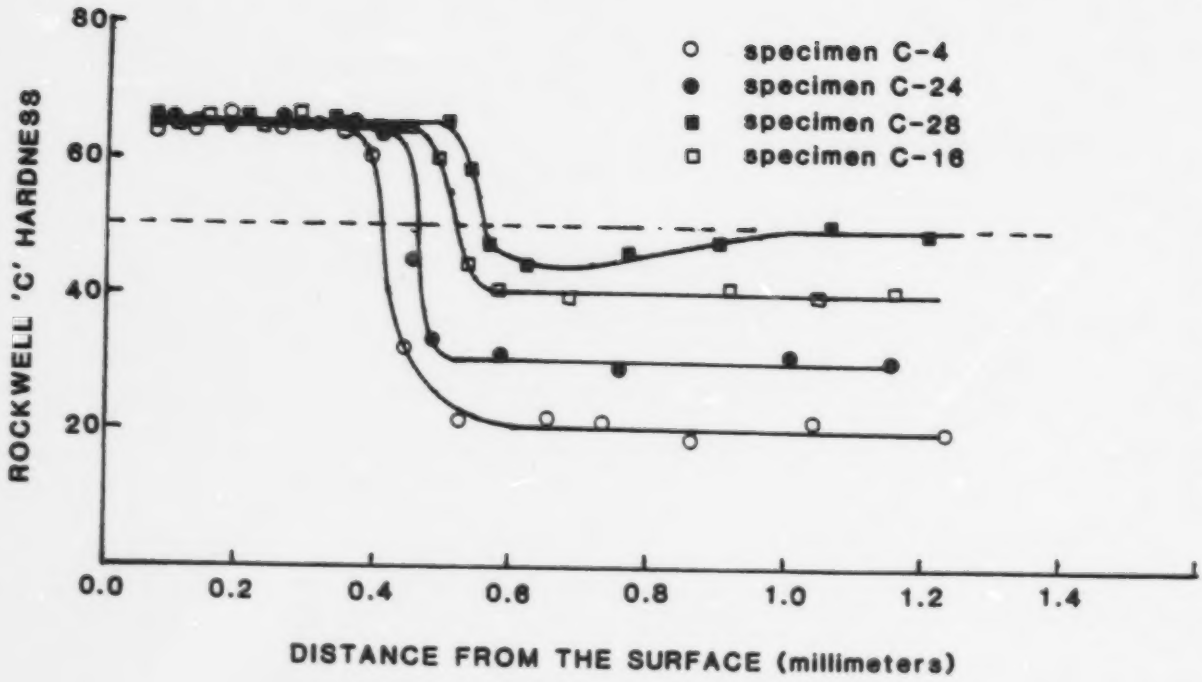

Figure 13: The Rockwell 'C' hardness versus the distance from the surface curves for the AISI 01 tool steel specimens irradiated by a 500 Watt laser beam and traversed at 0.21 cm/sec.

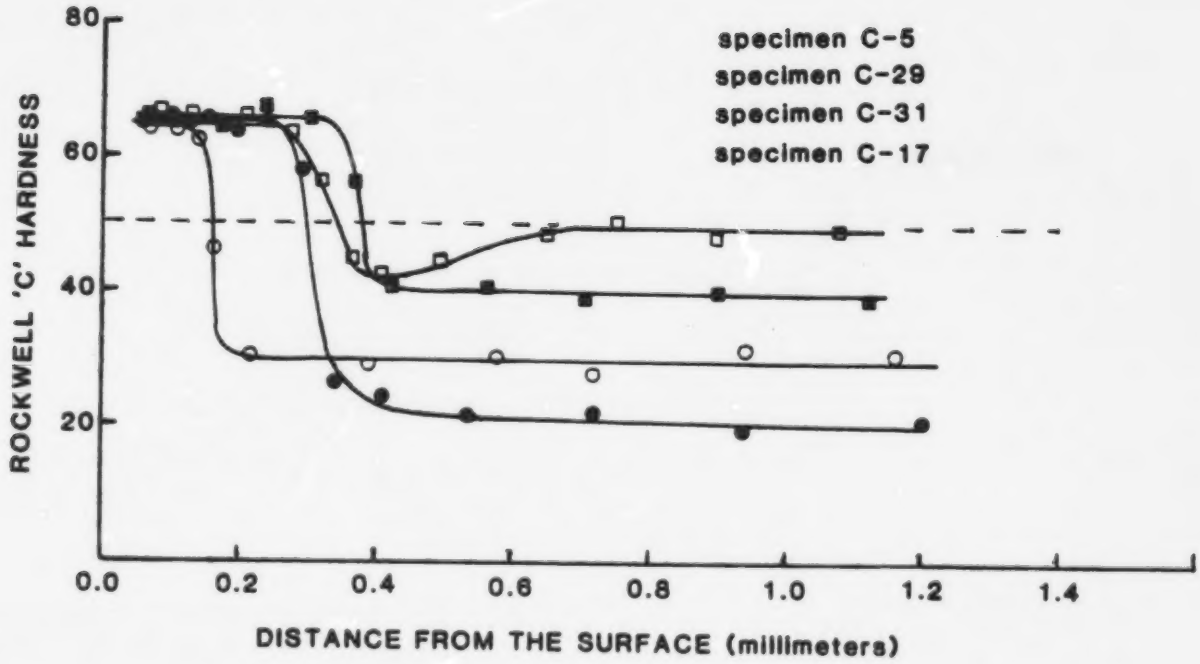

Figure 14: The Rockwell 'C' hardness versus the distance from the surface curves for the AISI 01 tool steel specimens irradiated by a 500 Watt laser beam and traversed at 0.42 cm/sec.

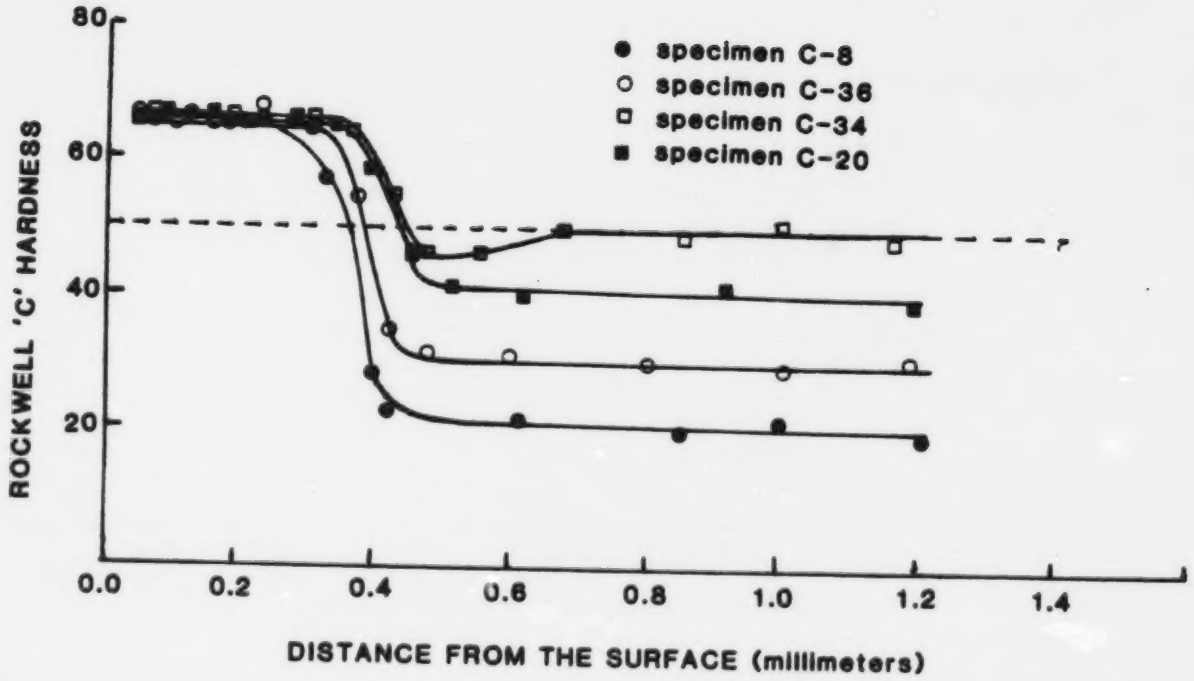

Figure 15: The Rockwell 'C' hardness versus the distance from the surface curves for the AISI 01 tool steel specimens irradiated by a 400 Watt laser beam and traversed at 0.21 cm/sec.

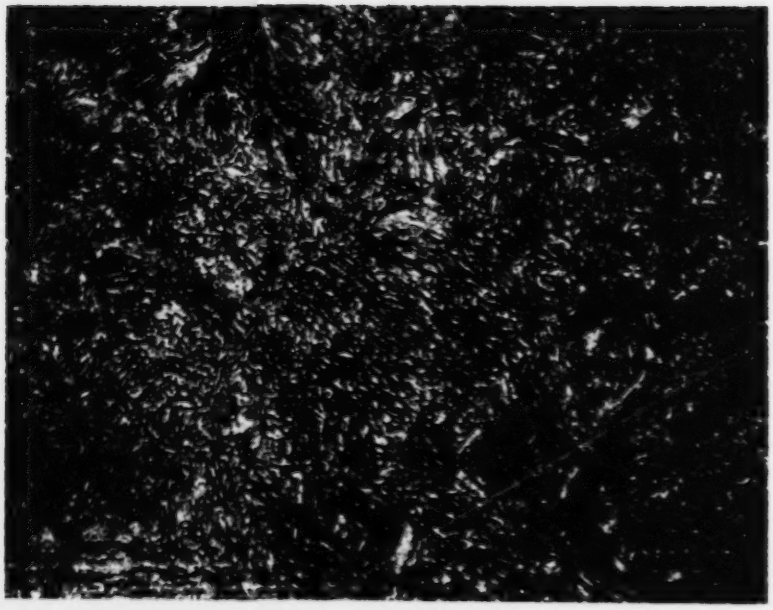

Figure 16: Typical microstructure of AISI 4340 steel quenched and tempered at 204°C.
Magnification - 1000X.

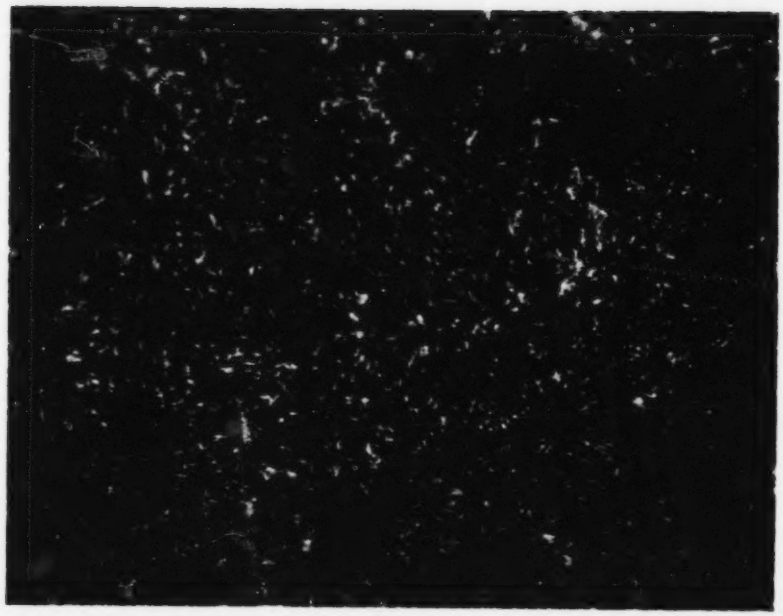

Figure 17: Typical microstructure of AISI 4340 steel quenched and tempered at 454°C.
Magnification - 1000X.

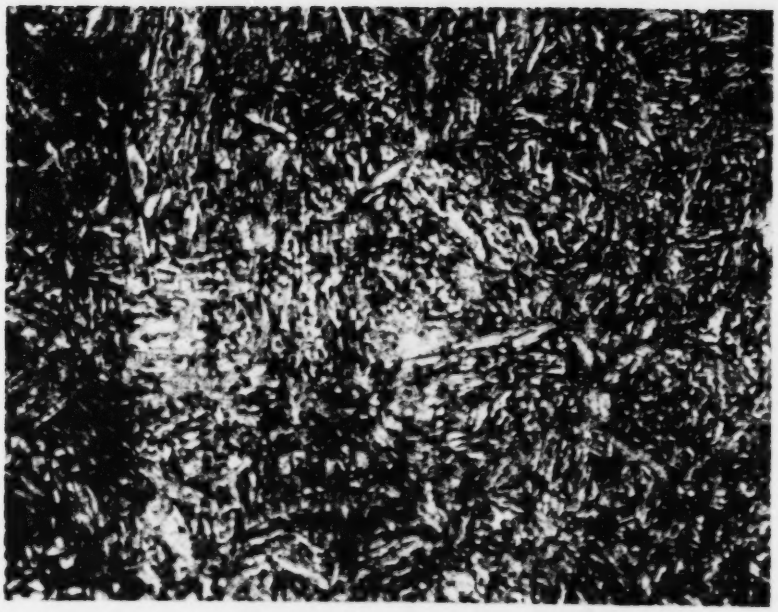

Figure 18: Typical microstructure of AISI 4340 steel quenched and tempered at 565°C.
Magnification - 1000X.

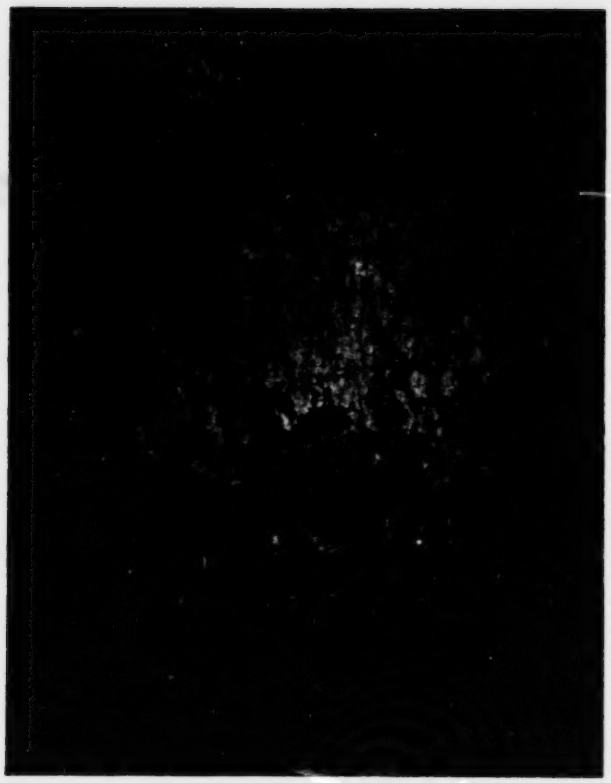

Figure 19: Typical transition zone for the AISI 4340 steel specimens hardened and tempered at 204°C. Magnification - 1000X.

Figure 20: Typical transition zone for the AISI 4340 steel specimens hardened and tempered at 565°C. Magnification - 1000X.

Figure 21: Typical transition zone for the AISI 4340 steel specimens in 'as received' condition, along with the micro-hardness indentations.
Magnification - 500X.

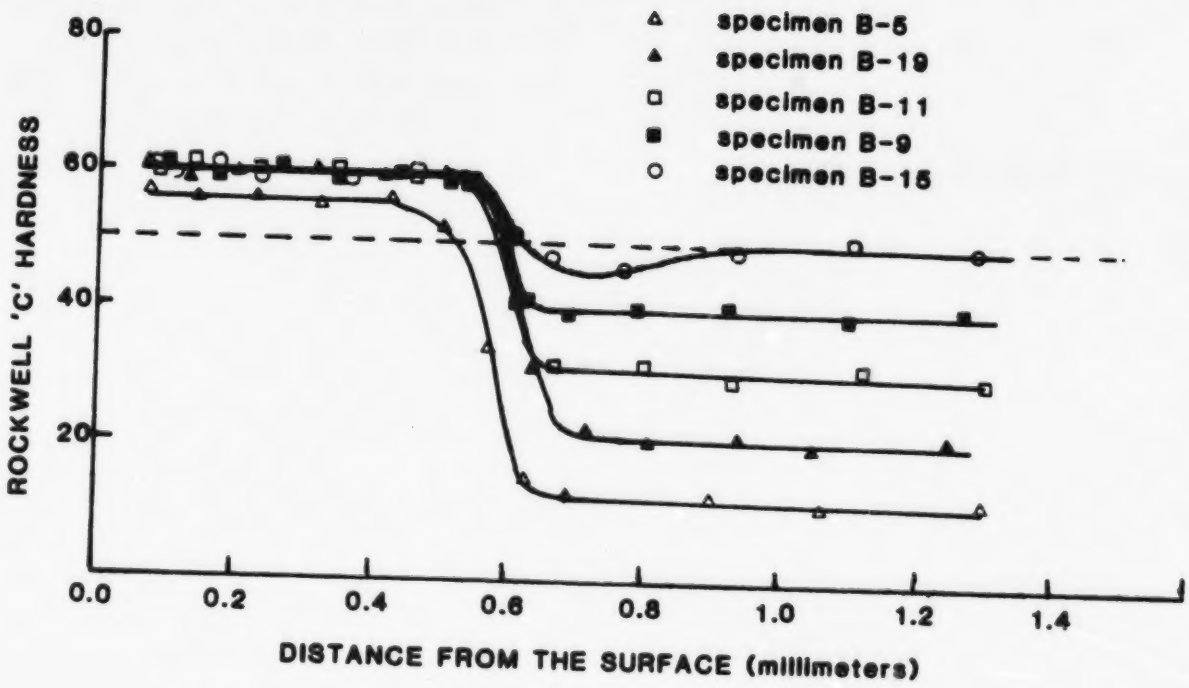

Figure 22: The Rockwell 'C' hardness versus the distance from the surface curves for the AISI 4340 steel specimens irradiated by a 600 Watt laser beam and traversed at 0.21 cm/sec.

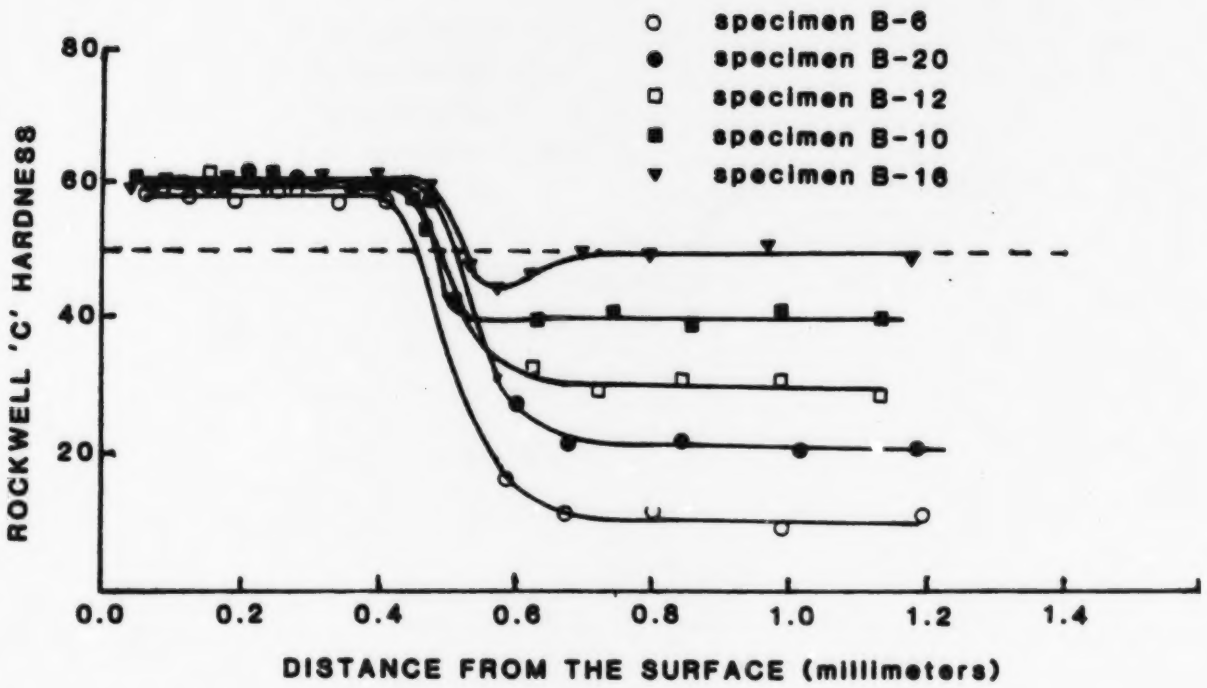

Figure 23: The Rockwell 'C' hardness versus the distance from the surface curves for the AISI 4340 steel specimens irradiated by a 600 Watt laser beam and traversed at 0.42 cm/sec.

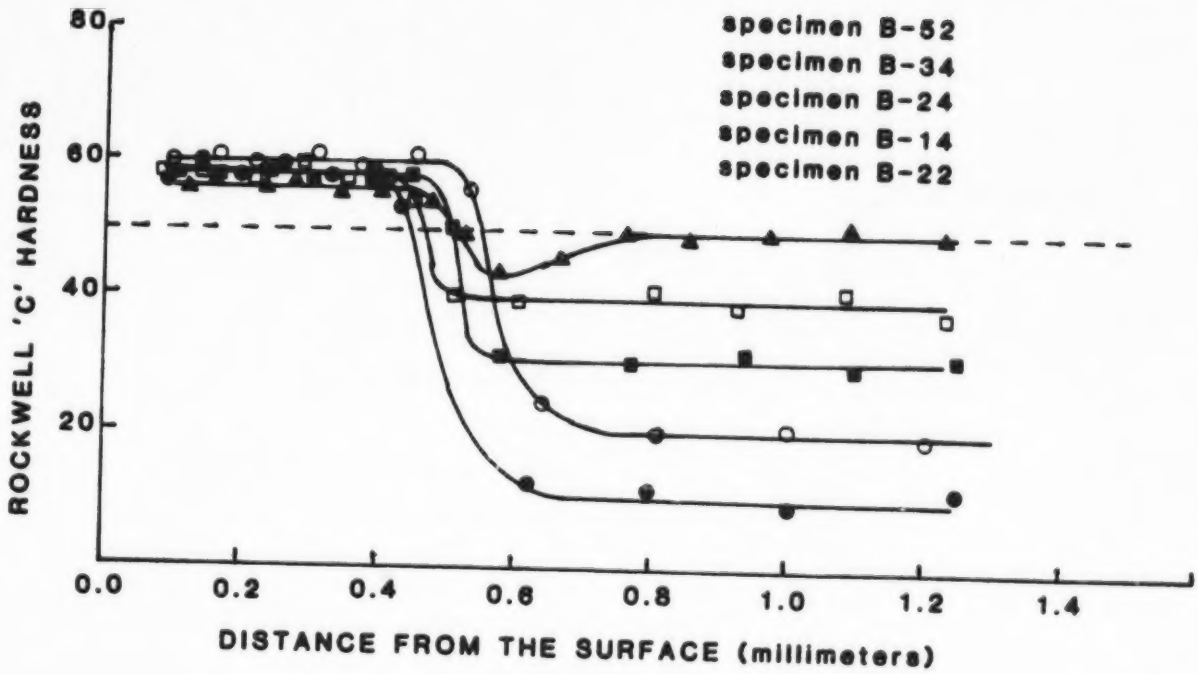

Figure 24: The Rockwell 'C' hardness versus the distance from the surface curves for the AISI 4340 steel specimens irradiated by a 500 Watt laser beam and traversed at 0.21 cm/sec.

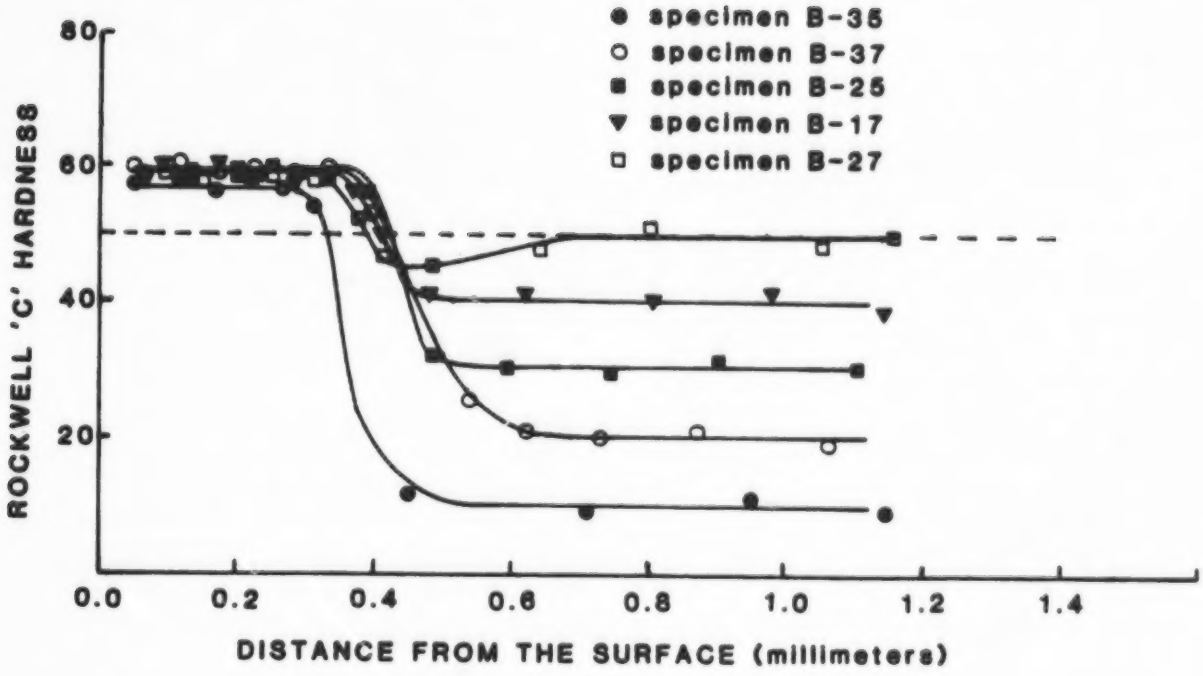

Figure 25: The Rockwell 'C' hardness versus the distance from the surface curves for the AISI 4340 steel specimens irradiated by a 500 Watt laser beam and traversed at 0.42 cm/sec.

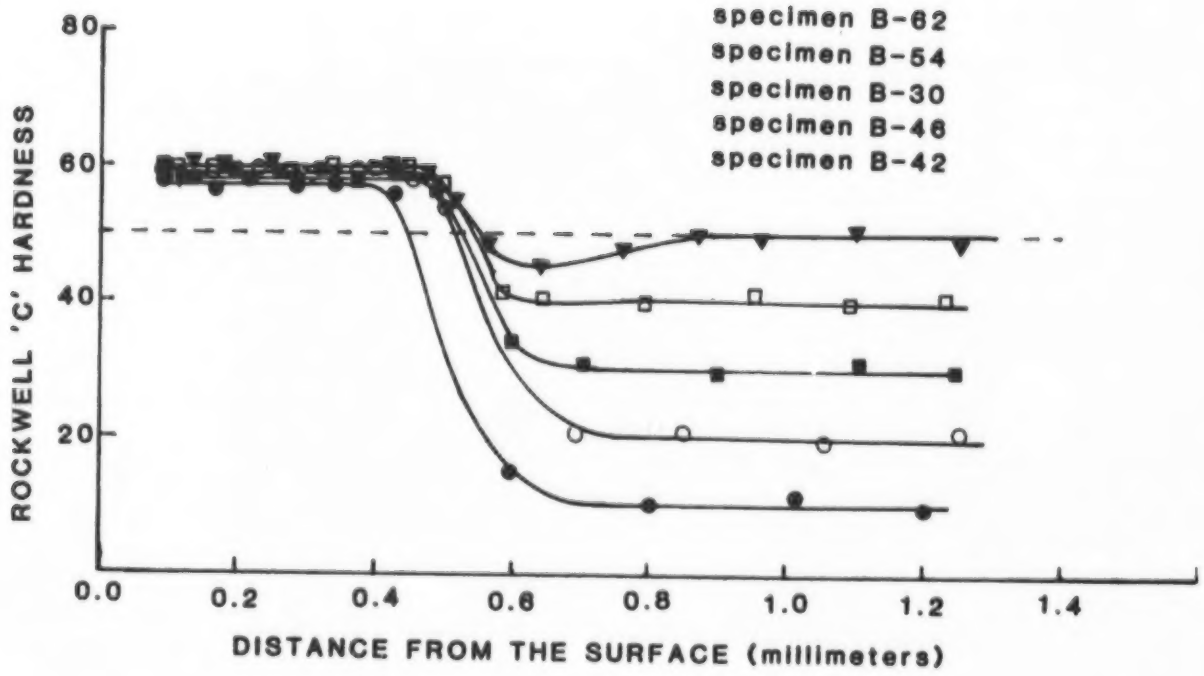

Figure 26: The Rockwell 'C' hardness versus the distance from the surface curves for the AISI 4340 steel specimens irradiated by a 400 Watt laser beam and traversed at 0.21 cm/sec.

Figure 27: Typical microstructure of the 'as carburised' case of AISI 1020 steel specimens.
Magnification - 500X.

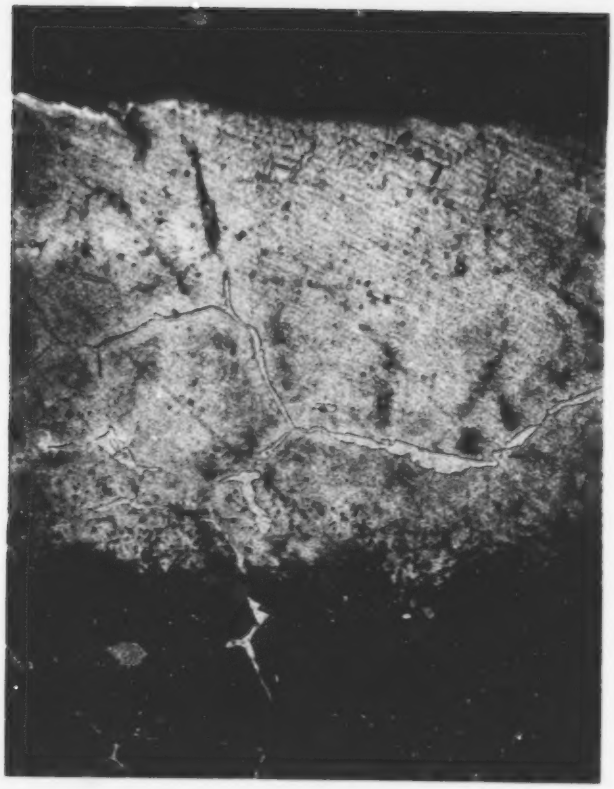

Figure 28: Typical laser hardened zone (lighter) and the carburized case (darker) for the 'as carburized' AISI 1020 steel specimens.
Magnification - 200X.

Figure 29: Typical microstructure of the laser hardened zone for the 'as carburized' AISI 1020 steel specimens. Magnification - 500X.

Figure 30: Typical laser hardened zone, the transition zone and the carburized case of the quenched and tempered carburized AISI 1020 steel specimens. Magnification - 500X.

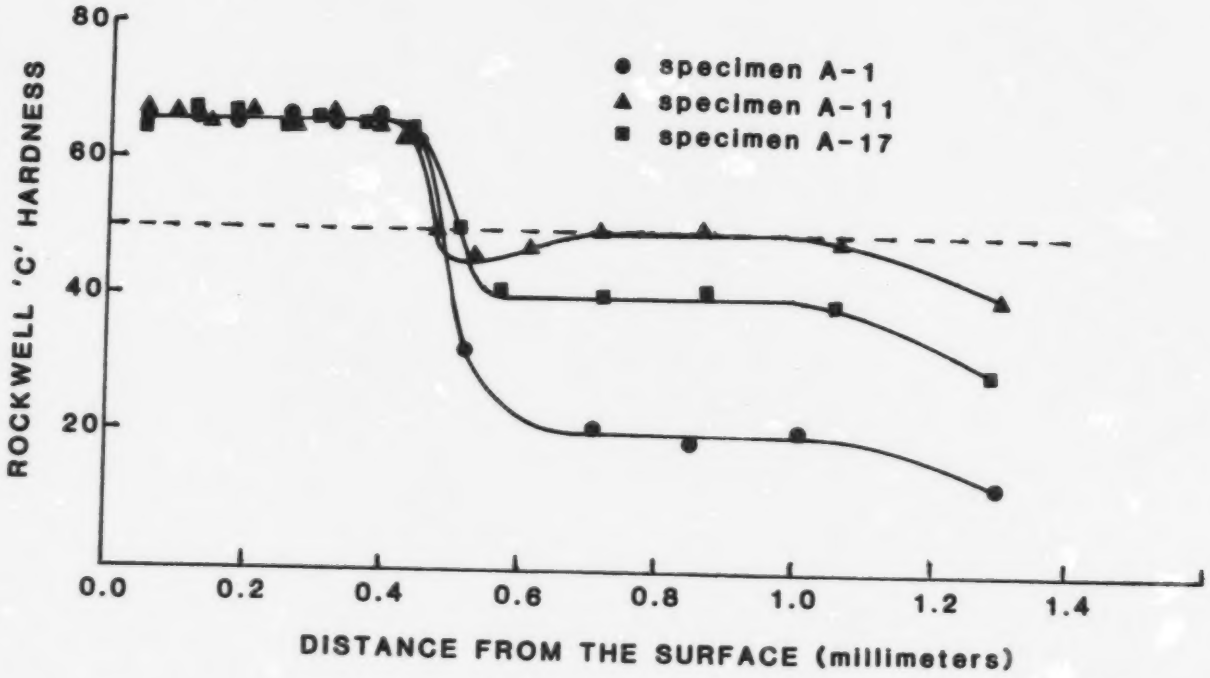

Figure 31: The Rockwell 'C' hardness versus the distance from the surface curves for the carburized AISI 1020 steel specimens irradiated by a 600 Watt laser beam and traversed at 0.21 cm/sec.

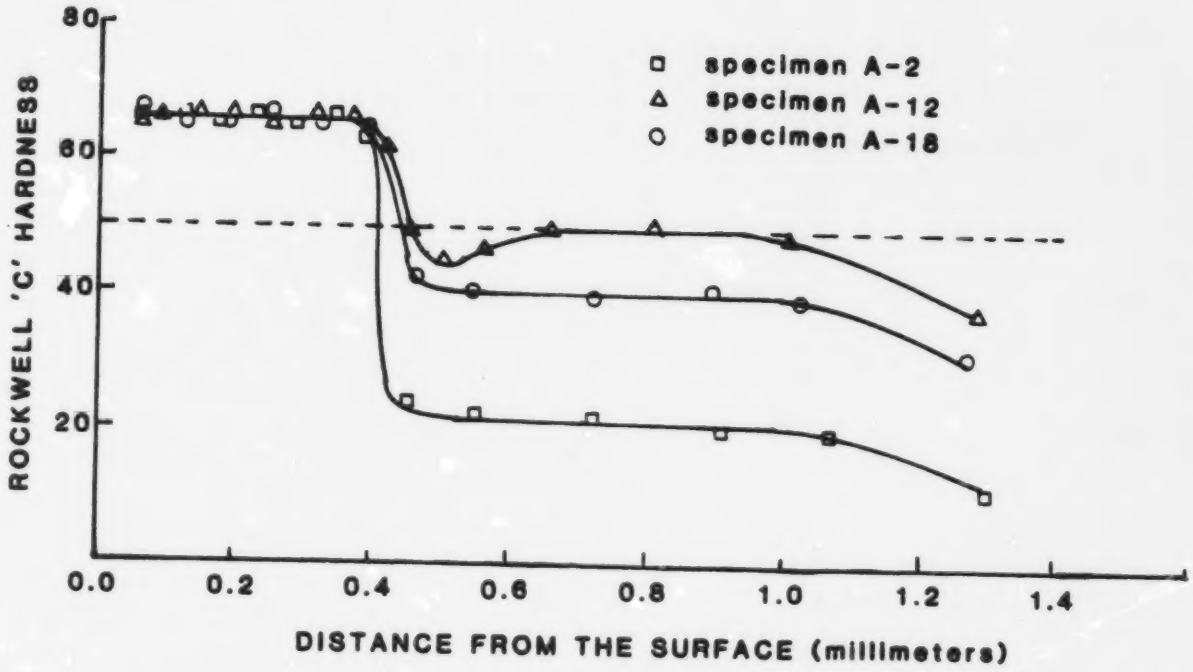

Figure 32: The Rockwell 'C' hardness versus the distance from the surface curves for the carburized AISI 1020 steel specimens irradiated by a 600 Watt laser beam and traversed at 0.42 cm/sec.

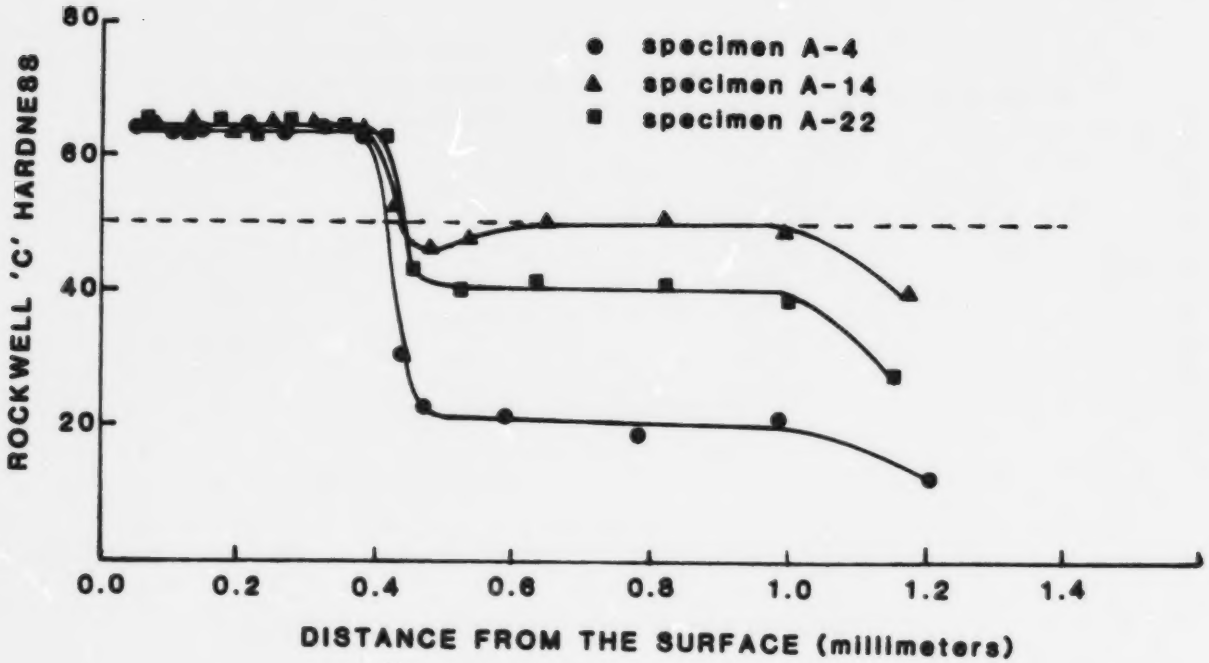

Figure 33: The Rockwell 'C' hardness versus the distance from the surface curves for the carburized AISI 1020 steel specimens irradiated by a 500 Watt laser beam and traversed at 0.21 cm/sec.

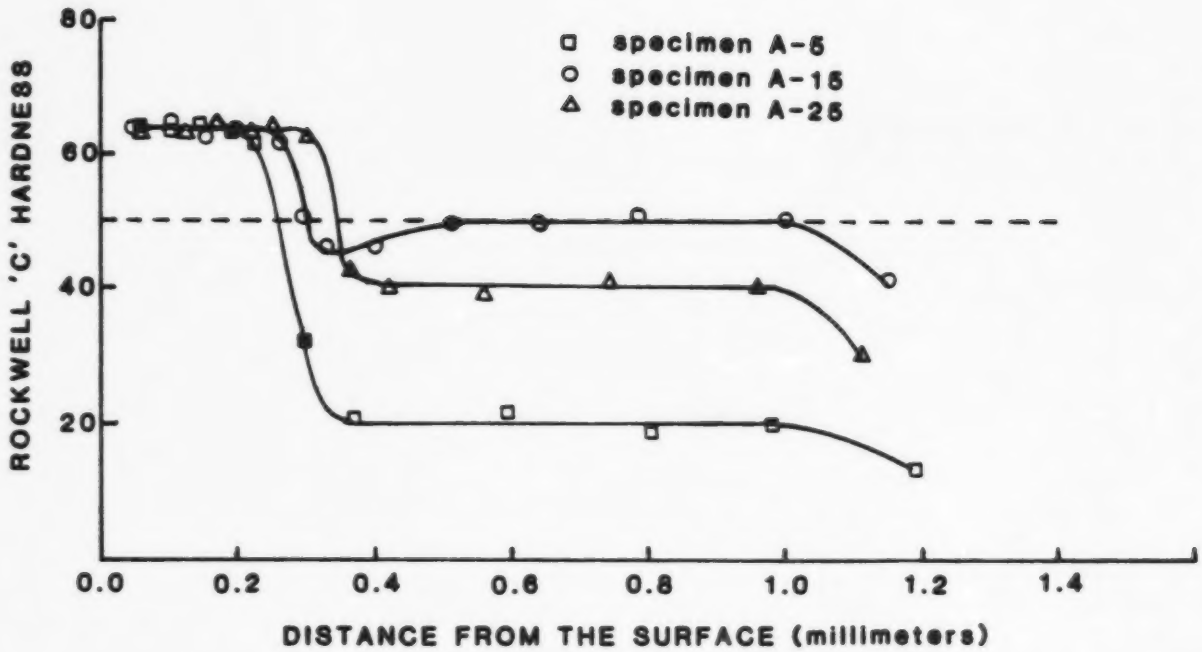

Figure 34: The Rockwell 'C' hardness versus the distance from the surface curves for the carburized AISI 1020 steel specimens irradiated by a 500 Watt laser beam and traversed at 0.42 cm/sec.

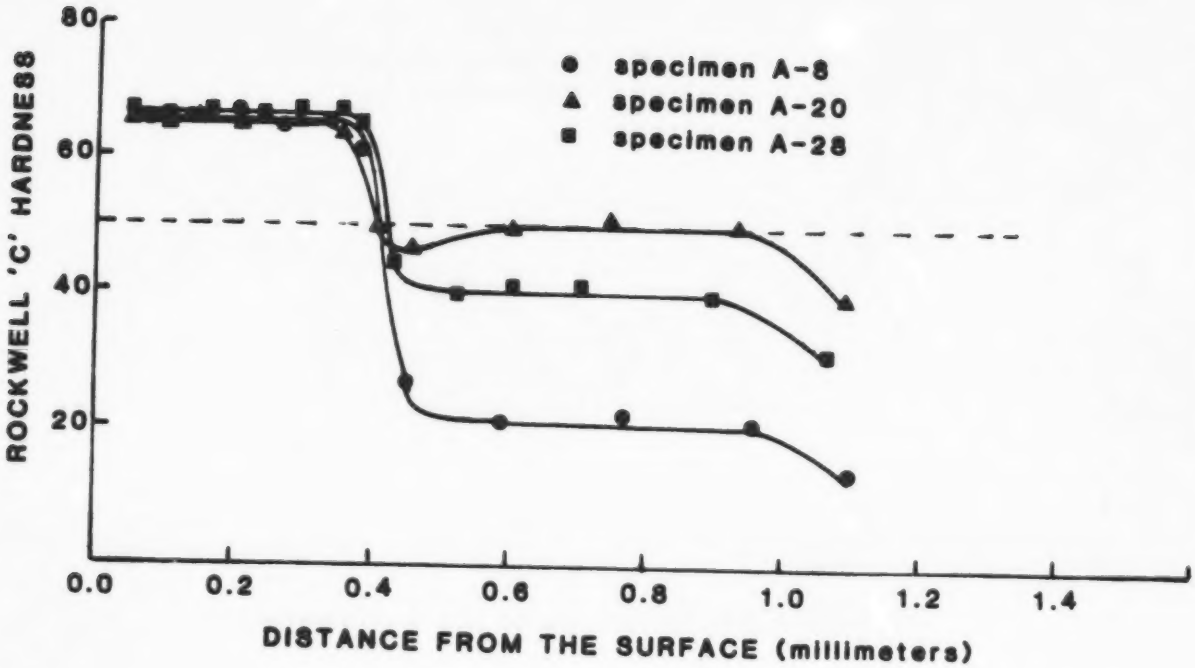

Figure 35: The Rockwell 'C' hardness versus the distance from the surface curves for the carburized AISI 1020 steel specimens irradiated by a 400 Watt laser beam and traversed at 0.21 cm/sec.